IMPACTS OF ELECTRIC PROPULSION SYSTEMS ON SUBMARINE DESIGN

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ABSTRACT

A theoretical study was carried out on the effects of replacing submarine turbine-reduction gear propulsion drive systems with an equivalent electric drive system. Alternating current (A.C.) and direct current (D.C.) systems were designed using computer based machine synthesis programs. The systems considered included direct drive motors operating at the speed of the submarine drive shaft and motors operating at higher speeds in conjunction with integral single stage reduction gears. Methods to improve the efficiency of the various motors for speeds other than rated speed were examined. The impacts of the electric system designs were evaluated in terms of the ability of a mechanical drive submarine design to accept the replacement of the mechanical components with the equivalent electric components and meet standard submarine design closure criteria.

All electric drive variants met the basic naval architectural feasibility requirements. Electric drive systems were heavier, required less arrangable volume and were generally less efficient than the mechanical baseline ship. Gear reduced electric systems were lighter and more than the direct drive, low speed motor based systems.

Electric submarine drive is a feasible alternative to conventional mechanical, locked train transmission systems. Electric drive installations carry penalties in terms of added weight and reduced propulsion plant efficiency that must be recognized and accepted by the ship designer.

Thesis Supervisor; Dr. James L. Kirtley Jr.
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Chapter One Introduction

Some recent studies have examined the use of electric propulsion on surface warships [1,2,3]. These studies have projected the possibility of significant volume and weight savings compared to mechanical drive system options of similar horsepower ratings. The author has found no recent studies that examine the impact of electric drive on the markedly different problem posed by submarine design. The purpose of this study is to extend the work done to submarines.

Modern submarine design is a complex, nonlinear optimization problem with constraints. The designer must continually balance ship operating depth, speed, and mission capability requirements against ship weight, volume, area and trim moment limitations. A tentative solution to this problem (a conceptual submarine design) is not feasible unless the equipment and structural material required to achieve the desired capabilities can be reasonably arranged and enclosed within the proposed submarine hull. This is complicated by the requirement of a submarine to be made neutrally buoyant and level trimmed while submerged over a wide variety of loading conditions. A submarine is said to be neutrally buoyant when the weight of the submerged submarine exactly equals the weight of water displaced by the submarine hull. This is attained using variable ballast tanks to fine tune the ship's weight . Level trim is the condition where there is no unbalanced longitudinal moment on the submarine while submerged. Unlike surface ships which experience a leveling moment due to the free surface of the water, a submerged submarine must be able to adjust its "trimming" moment in order to remain level when submerged. This is also done with variable ballast tanks.

Most modern naval submarines are based on turbine driven, mechanically coupled propulsion systems [4,5,6,7]. This design approach limits the flexibility in arrangement of the engineering spaces since the entire drive train from turbine to propulsor must be mechanically connected in order to transmit the propulsion power to the water.

Electric propulsion provides an option in which it is potentially possible to separate physically the source of propulsion power (the turbines) from the ship's prime mover. Instead of turbines directly coupled to the shaft, electric turbine generators would provide electrical power to a main motor which would drive the shaft. Such a design could conceivably eliminate the need for the lock train, serially coupled mechanical systems and permit more efficient use of the submarine's very tightly constrained interior volume. (Locktrain refers to a means of coupling mechanical systems where gearing is permanently coupled together).

1.1 Report Organization

The report is organaized in the following manner.

Chapter One discusses the basic differences between surface ship and submarine design,types of electric motor that could be used to advantage on a submarine and how electric drive might be expected to affect the total submarine design. Particular emphasis is placed on how these differences could be expected to affect the type of optimization objective function used.

Chapter Two discusses the selection and development of the basic models, the optimization technique used and the establishment of the constraints on the motors .

Chapter Three provides an introduction to the basic principles of submarine design and develops the mechanical transmission submarine design that will serve as the "experimental control" of the study.

Chapter Four addresses the synthesis, design and selection of the candidate A.C. synchronous motors for the study. Both direct drive and gear reduced motor designs are considered.

Chapter Five investigates techniques by which the electrical efficiency of the motors designed in Chapter Four might be improved for speeds other than the rated or design speed of the motors. A discussion concerning why such off-design-point efficiencies are important when a motor is considered for use as a submarine propulsion system is included.

Chapter Six repeats the effort of Chapter Four for D.C.homopolar motors.

Chapter Seven integrates the "best" motors from the preceding chapters into the basic submaine platform developed in Chapter Three and analyzes the naval architectural impacts caused by the change of transmission systems.

Chapter Eight reviews and summarizes the results of the study and presents the author's findings. Additionally, recommended areas for futher study growing out of the findings of this study are presented.

Where appropriate, appendices are included to provide background and additional detail.

1.2 Submarine - Surface Ship Design Differences

Modern submarine design is fundamentally different from conventional surface ship design. Therefore, the advantages derived from electric propulsion systems on surface ships do not necessarily apply to submarines.

Surface Ship Design:

The majority of modern surface warships (exclusive of some large aircraft carriers and cruisers) have conventional, fossil fuel burning propulsion drive systems that employ gas turbines as the prime mover for the ship's propeller. The transmission is mechanical and locked train from the turbine to the propeller.

The use of mechanically coupled gas turbine drives imposes significant volume and weight penalties on the ship. These penalties are associated with the gas turbine ventilation intakes and uptakes, and with the shafting connecting the ship's propeller to the turbine. Gas turbines require huge volumes of air to operate. Therefore, the gas turbines are usually located directly underneath the main deckhouse stacks to minimize the "lost volume" for the intakes and uptakes. Connecting the turbines to the shafting restricts the turbines to locations low in

the ship. This results in more volume being dedicated to gas turbine support and to long runs of shafting from the turbine to the shaft/hull exit point that might otherwise be reallocated for other ship needs or eliminated from the ship .

Gas turbines have other, indirect effects on the size and weight of a surface ship. The fuel load that a ship is designed to carry is based upon the distance it must be able to travel without refueling at the endurance speed. Marine gas turbines are single direction of rotation machines. In order to change the speed of the ship or to back down, gas turbine ship designs employ controllable, reversible pitch propellers (CRPP). When reversing the direction of the ship's motion without reversing the direction of shaft rotation, CRPP's mechanically reverse the pitch of the propeller blades. The problem with this is that CRPP 's are not usually the most efficient possible propeller design for the particular ship's endurance speed. Typically, the most efficient designs are fixed pitch propellers built with a blade pitch that would preclude reversing the pitch. Therefore, CRPP's generally lower the overall propulsion plant efficiency. This reduction in efficiency requires that additional fuel be loaded in order to meet the ship's endurance requirements.

Electric Drive Applied to Surface Ships :

Electric drive permits decoupling the propeller from the gas turbines. This eliminates the need for much of the shafting and permits placement of the gas turbines higher in the ship reducing the volume and weight penalties. A smaller hull is required to support the same payload. This in turn reduces the total drag the ship must overcome to drive itself through the water. In addition, although electric motors impose an additional energy conversion step in transmitting the generated power to the water, they are inherently reversible. This permits the use of an optimized fixed pitch propeller which increases the overall efficiency of the propulsion system. The end result is that the required fuel load is markedly reduced for a given ship payload (which again reduces the size and cost of the ship). In summary, use of electric

propulsion provides significant resource savings and design flexibility when applied to surface warships.

Submarine Design [8,9]:

In the United States, modern submarines have nuclear powered, steam turbine driven, mechanical transmission propulsion systems [4,5,6,7]. The vessels are bodies of revolution about the longitudinal axis of the ship. When underway, the entire hull is fully submerged so that the entire hull contributes to ship drag. (These bodies of revolution are based upon the optimum hydrodynamic shape for minimizing the drag force on the hull.) To reduce drag, the hull's surface area (and therefore its volume) must be significantly reduced. However, since submarine hull buoyancy must equal the weight of the submarine in order to make the design neutrally buoyant, any reduction in hull volume must be accompanied by a matching reduction in the submerged weight of the ship.

Once the required power of the ship is determined, the weight of the reactor systems, steam systems and reactor support and steam plant support systems is fixed. Nuclear fuel load is fixed by the total stored energy in the fuel required to support the ship's expected operational tempo between nuclear refuelings. Small variations in required power due to efficiency or fine tuning of a speed requirement do not significantly change the weight of the propulsion plant once these gross power requirements are set. The steam driven main propulsion turbines are reversible and speed variable, permitting the use of optimized, fixed pitch propeller designs.

Conclusions:

Electric drive advantages on surface ships accrue from indirect affects that result from the improved arrangement of the propulsion equipment and improved propulsor efficiency. In contrast to surface warships, electric drive designs for submarine have little if any indirect effects, while directly affecting only those components that actually comprise the propulsion

train. These components are the main propulsion turbines, the reduction gears and the associated additional shafting. They comprise about 15% of the total propulsion and electrical system weight for a typical submarine. Propulsion and electric plant systems comprise approximately 25% of the submerged displacement of a modern submarine. Thus, only 4 to 5% of the submarine's weight is affected by use of electric drive. The point is that one must not expect that electric drive will, *a priori*, impact the design of submarines in the same manner as electric drive impacts surface ships.

The key difference is the flexibility of arrangement that exists on a surface ship as compared to a submarine. As an example, consider a 10,000 Long Ton (1 long ton equals 2,240 pounds and is a standard naval architecture unit of measure. Coincidently, it is also very nearly equal to 1 metric ton or 1,000 kilograms) displacement surface ship as compared to a 10,000 LT submerged displacement submarine. By Archimedes Principle, both vessels displace 10,000 LT of seawater in order to float. For the submarine, this displaced volume represents the entire available volume of the ship, or approximately 350,000 ft^3 of volume. For typical submarine designs, this would correspond to a 450 ft submarine with a 33 ft diameter. A 10,000 LT surface ship displaces the same amount of seawater, but this only represents the submerged volume of the ship or less then half of the available arrangeable volume since the ship also has hull volume above the waterline and the volume in the deckhouse superstructure to use for arrangements.

1.3 Review of Electric Drive

Electric propulsion on submarines is not a new concept. Actually, the "new" concept is turbine mechanical drive. Almost since submarines changed from the manually powered designs of the Eighteenth and Nineteenth Centuries, the need for reliable, non-air-breathing propulsion systems have led naval architects to use large electric storage batteries to provide the energy needed to drive the ship while submerged. Space and weight limitations forced the

designer to use the same main motor for both surfaced and submerged operation. Thus evolved the Diesel Electric Submarine, the undersea threat of both World Wars and the mainstay of most modern submarine forces throughout the world. Typical shaft horsepower ratings for diesel electric submarines are anywhere from 1500 - 6000 HP [4,5,6,7]. The large marine diesel engine generators provide power for propulsion when operating surfaced or snorkeling and to charge the main storage batteries in preparation for submerged operation. Submerged endurance then is a function of battery capacity (a design parameter) and battery discharge rate (an operational parameter).

With the advent of nuclear power in the 1950's and 1960's, most submarine design moved away from electric drive towards mechanical systems. In order to take full advantage of nuclear power, submarine shaft power levels are far in excess of any previous submarine design. Additionally, submarines require the flexibility to instantly operate at any speed between zero and full power speed. Electric motors of the day capable of the power and speed flexibility (such as commutated D.C.) were heavy, bulky and difficult to maintain within the tight confines of a submarine. Alternatives such as A.C. motors are usually smaller, lighter and easier to maintain, but have the disadvantage of being difficult to change speed , particularly throughout as broad a speed range as required by a submarine.

Recent advances in electric machine design and power electronics have made the use of large electric motors as submarine main propulsion systems appear feasible.

Two systems in particular appear to hold promise for submarine use, but for different reasons:

- Conventional Homopolar D.C. motors have the advantage of being phase upgradable to superconducting machines of similar design if high temperature superconductors become feasible. Power sources and control systems for a comparably rated superconducting homopolar motor should not require

significant changes, so a simple propulsion platform replacement appears to be an option to superconducting drive backfits.

- A.C., Water Cooled Stator, Synchronous Motors provide a great deal of commonality with proposed surface warship designs. In addition to the typically smaller size and weight of A.C. components (as compared to D.C. systems), there are potential cost savings in both procurement and life cycle management of these systems if the number to be bought can be combined with procurement and support of surface warship systems.

A.C., Water Cooled Stator, Induction Motors offer similar advantages to the synchronous machines, but were not studied for two reasons:

a. Submarine propulsor speed control requires a degree of precision that is more difficult with a slip controlled machine than with a synchronous machine.

b. Davis [1] results indicated that synchronous and induction motors were comparable in size, weight and efficiency so that the submarine design impacts of the two motor selections would be of the same order.

1.4 Optimization

Most real decisions involve making tradeoffs among a variety of possible strategies in order to achieve the best possible result. The result , or "objective" can be to maximize or minimize some parameter, while the strategies can involve the allocation of resources needed to achieve the various possible outcomes.

Optimization is a process by which the decision process is modeled mathematically in order to evaluate possible strategies efficiently and determine the "best" decision. In this process, the objective goal is modeled by a single objective function that in some way provides a numeric measure of how well the goal was achieved. The strategies can be related to constraints upon how the goal is obtained. In many cases this would represent the limitations

on resources a manufacturer might have in a selection of fabrication processes or in allocation of assets between different ongoing projects. In the design world the objective might represent the new device's required output or efficiency while the strategies or constraints might involve controlling fabrication time, reducing material costs or ensuring that the dimensions of the device would permit it to fit in a preexisting system.

The concerns for a constrained optimization of a submarine propulsion motor closely match those discussed by Davis [1] and will not be repeated here. The only difference will be that because of the extremely restricted volume for arrangability on submarines, volume available for the motor and the gross dimensions of the motor are hard and fast constraints. The motor must,first and foremost, fit within the limiting dimension of the submarine hull (usually the internal hull diameter). A motor that will not fit into the hull is not a feasible solution.

The final concern is what to optimize. Davis[1] used a parameter called Effective weight as an objective function. In simplest terms, the best design for a given ship propulsion power level is the lightest weight design. The ship power requirement is the mechanical power turning the shaft at the output of the motor. Upon closer examination, it becomes apparent that the efficiency of the motor will affect the size of other propulsion plant components in order to achieve the required output horsepower from the total power plant.

Effective Weight is used as the objective function for the design of the motors encompassing both the actual motor weight and a factor to allow for the size of the propulsion plant fluctuation based on the changes in motor efficiency caused by variation in the physical parameters of the motor

$$\text{Effective Weight} = \text{Motor Weight} + k_\eta(1 - \eta) + k_v v$$

where η is the overall efficiency of the motor design, k_η is the weighting factor for efficiency, v is the envelope volume of the motor and k_V is the weighting factor for motor volume. The weighting factors were obtained from changes in propulsion plant weight for marginal changes in motor efficiency and volume. Appendix A contains a derivation of these relations and numerical evaluations of k_η and k_V.

Chapter Two: General Considerations

2.1 General Modeling Considerations

This study considers only the steady state behavior of the candidate motor systems. The changes in the size and weight of a large motor resulting from adjustment of its dynamic response are relatively small when compared to the impact of the motor itself. The impacts on the design of the submarine of such changes would not cause a feasible motor design (based upon the steady state analysis) to become infeasible.

Synchronous motor modeling was done using the techniques and computer codes developed by Davis [1] with some minor differences in approach. These differences are primarily the result of more detailed thermal effect analysis and are discussed in detail in the applicable chapters.

The design method leaves the number of winding turns and the number of rotor and stator slots unspecified. The units for the motor electrical parameters were "normalized" to account for the actual current densities and power ratings of the motors. These normalized units are "volts per turn", "ampere-turns" and "ohms (impedance) per turn squared". Power is measured in watts.

The number of pole pairs in a machine was varied until a trend of diminishing improvements was observed.

Homopolar motors were modeled as drum style machines using a design program [10] provided by the David Taylor Research Center (Code 271) in Annapolis, Maryland. The number of current collectors for the transfer of current from the armature rotor to the armature stator are in discrete pairs. The design technique "deterministically builds" a motor with the specified number of current collectors. An initial design guess is obtained by first ensuring adequate power is provided to the motor (ie current and voltage specification). A closed solution is obtained by then iterating the MMF magnetic circuit parameters versus the terminal

output that result. Motor designs were developed for collector configurations from twenty to forty pairs. The optimum design was obtained by applying the Effective Weight objective function to the resulting designs.

2.2 Optimization Technique

The optimization of an electric motor is done over a multiple dimension variable space. Changes in the gross dimensions of a machine affect the tightly coupled electrical parameters of the machine and thus its predicted performance. For example, changes to the gap separation between the rotor and stator of an A.C. motor will change the magnetic field (by Ampere's Law) , the synchronous reactance of the motor, and the thermal performance of the motor. Such interdependences greatly increase the complexity of designing the "best" possible motor in a time and effort efficient manner.

The technique used by Davis [1] for the design of A.C. machines is a combination of the Monte Carlo and steepest descent schemes. A random number generator is used to establish a "seed" design point for the machine dimensions (subject to the constraints imposed). A series of random steps in all variable directions is taken about the seed point. For each of the steps, the effective weight is calculated and the lowest of these established as the new design point. The process is repeated until the improvement between design points is less than a specified tolerance. At this point, the step size is halved and the process is repeated. The process repeats with step size being halved up to ten times with the lowest effective weight being presented as the output design.

The synchronous design program assigns randomly selected values for the stator current density, rotor radius, rotor/stator air gap, and the stator and rotor slot space factors. Additionally, the code was modified to randomize rotor current density while fixing the synchronous reactance, in order to check the sensitivity of the optimization to the set of

variables selected. Back iron dimensions were sized to keep the flux levels in the iron just below saturation when operating at rated power.

2.3 Constraints

2.3.1 Electrical Motor Design Constraints

The following table summarizes the constraints imposed on the design optimizations.

Table 2.1 Electric Motor Constraints

Minimum Air Gap Flux Density:	1.05 Tesla rms
Maximum (saturation) Flux Density	1.8 Tesla rms
Maximum Rotor Radius	2.0 meters
Maximum Motor Envelope Radius	3.0 meters
Maximum Rotor Tip Speed	200 meters/sec.
Maximum Rotor Slot Depth	33% of rotor radius
Maximum Synchronous Reactance	2.0 per unit
Power Factor	0.8

Flux density limitations are based on minimum acceptable fields for motor operation and the saturation characteristics of the magnetic steel selected for the motors, 26 gauge M19 steel. M19 is a typical high grade magnetic sheet steel used in electric motor fabrication and its properties were found in USX technical data [11].

Envelope radius ensures that the designed motors will fit within the enclosure of the submarine in the vicinity of the shaft sterntube. The hull radius of the mechanical transmission submarine design where the motor will be installed is 13 feet. Allowing for the structural hull framing, the free space for the motor will be approximately 22 feet in diameter. The three meter radius of envelope limit will allow for the inclusion of support structures to hold the motor inplace.

Rotor tip speed ensures that the structural strength of the connection of the rotor bar to the rotor is not exceeded. This is consistent with standard Navy design practices for rotating electrical equipment design. Rotor slot depth is constrained to ensure that some reasonable portion of the rotor is solid to transmit the mechanical torque the motor is generating.

Synchronous reactance is an impedance between internal voltage and machine terminals. High values of synchronous reactance result in larger than necessary field current adjustment under load, inferior dynamic performance and low transient stability limits. The limit of 2.0 per unit was taken from as built machines. The power factor of 0.8 is consistent with standard design practices.

2.4 Other Considerations

The weight calculated for the motors was adjusted by three percent of the rotor weight to account for the weight of the bearings and bearing caps on the motor shaft. Motor frames and foundations were estimated to be ten percent of the motor's weight and volume calculated values. The envelope weights and volumes (ie motor, foundations, frames and bearings) were used in the decision analysis.

Efficiency is the ratio of the output power to the sum of the output power and the various losses accrued in generation of the output. In this study, the losses accounted for are rotor and stator copper resistance losses, hysteresis losses and eddy current losses. The copper resistance losses result from the imposed electric currents that make the machines work. The other two loss modes result from circulating currents in the magnetic steel used in the fabrication of the machines.

Eddy currents result from time varying magnetic fields and oppose changes in flux density. Eddy current losses are proportional to the square of the electrical frequency and the square of the peak flux density. Rotors and stators are built of thin laminations of the the

magnetic steel separated by insulating varnish in order to limit the axial magnitude of these currents.

Hysteresis losses are the result of the magnetic material being driven along the B-H hysteresis curve by the variation of the current due to the electric frequency. The magnitude of the loss is proportional to the area of the hysteresis curve, the volume of material used to build the machine and the electrical driving frequencies.

USX has developed parametric equations to estimate the losses associated with hysteresis and eddy currents in watts per pound of material.

$$\text{Hysteresis Losses: } ph = \frac{0.01445\,\beta\, f\, B_r\, H_c}{D}$$

$$\text{Eddy Current Losses } pe = \frac{0.4818\, N\, B_m^2\, t^2\, f^2}{\rho\, D}$$

where:

β	=	the hysteresis loss factor (ratio of the actual area of the hysteresis curve to the square loop formed by B_r and H_c
f	=	the electrical frequency in Hertz
B_r	=	the residual induction in kilogauss
B_m	=	the saturation or maximum flux density in Tesla
H_c	=	the coercive force in oersteds
D	=	the density of the steel in grams per cubic centimeter
ρ	=	the electrical resistivity of the steel in microohm-centimeters
N	=	the anomalous loss factor
t	=	the lamination thickness of the steel, 0.014 inches for M19 steel

With the exception of the lamination thickness and the electrical frequency, the parameters above are physical constants of the material used in the fabrication of the machines. The values are parametric in nature and do not reflect effects due to metallurgical variation in the processing of the steel.

Chapter Three: Mechanical Submarine Baseline Design

3.1 Basic Design Technique Discussion

Historical beginnings

New submarine design is generally evolutionary in nature, that is, a great deal of what goes into the design is based upon recent successful projects. With the exception of some particularly radical design feature, such as the "teardrop" hull design on USS ALBACORE or the initial use of nuclear powered propulsion systems on USS NAUTILUS, the basic design and system tradeoffs involved show a great deal of similarity to previous designs. There are both physical and practical reasons for this.

First, the submerged weight of the total ship must equal the weight of the water that the hull and impenetrable appendages (the so called "everbuoyant volume") displaces. The initial determination of the ship gross characteristics (overall length or "L_{OA}", hull diameter or "D", and basic shape coefficients) impose a rigid set of constraints on the design. The weight of materials used, the types of equipment installed, the amount of arrangeable volume and "floor area" are resources that must be carefully monitored and controlled if the ultimate design is to be feasible.

In a practical vein, the performance characteristics of the previous ship designs have been carefully documented and studied. This large, detailed knowledge base indicates that the submarines consistently performed as they were expected to when in the early design phase. This consistency of performance permits the designer to make reasonable statements on the performance and cost of the new submarine, years in advance of the first unit going to sea, so long as the assumptions built into the design methodology are met.

The problem with this type of design procedure is that any large deviation from the current body of knowledge (such as a modern day ALBACORE or NAUTILUS) are viewed with skepticism, since the outcome can not be as accurately predicted.

Design Progression:

The submarine design process is a stepped progression that solves the design problem to that level of detail and complexity needed to support the next key decision. These decisions usually involve whether or not to proceed further down the design path (and to incur the associated expense), but could also involve answering questions on how a capability might be implemented on a submarine platform (such as the POLARIS Sea Launched Ballistic Missile program).

The initial step is Feasibility Study. The goal of Feasibility Study is to answer the questions "Can it be done?" and "Will it float?". The studies are first order involving gross weight-buoyancy balances and only large or critical component arrangement. Ship costs are estimated, but only very crudely (± 100%). The most promising designs can be studied in greater depth and detail. In particular, the impacts of possible key design tradeoffs can be studied to determine how the choices affect the ship.

The next step in the process is Preliminary Design. At the end of Preliminary Design, the key decisions for equipment and capability have been made and "frozen". The study deliverables include detailed arrangement drawings, a detailed weight - buoyancy estimate and a cost estimate suitable for presentation in the Congressional Budget Request. Between fifty and one hundred drawings have been developed and form the basis of the next phase.

Following Preliminary Design, Contract Design develops the drawings, specification lists, cost estimates and test plans needed to present a "biddable package" to Industry for the final detailed design and construction of the new ship.

Detailed Design is the final product that will be used to fabricate the actual ship. Anywhere from fifty to one hundred thousand drawings and one to two million parts will be used to finish a submarine.

It is important to realize that the above efforts are all "pencil to paper" efforts; that is, done without the benefit of a computerized, synthesis tool. For surface ship design, the

Advanced Surface Ship Evaluation Tool (ASSET) used by Davis [1], can be used to investigate how changes in technology affect the balance of a warship. There are few ways, short of going to the expense of building a new, one-of-a-kind ship, available to evaluate radically different submarine principles or features. Considering the current cost for a new submarine ($1.1 Billion dollars (Fiscal Year 1989 dollars) per ship at full production for the new SEAWOLF Class [12]), it is difficult to justify this expenditure on a potential "failure" in design.

The effort in this thesis investigation is a detailed version of the Feasibility Study with tradeoffs revolving around the use of electrically transmitted propulsion drive systems. The tradeoffs are made to a baseline design developed using the parametric procedures in [8,9]. Due to the prevalence of mechanically driven submarines in the source database,these parametrics assume a mechanically transmitted propulsion drive system. The applicable mechanical drive system components are then replaced by the equivalent electrical transmission drive systems discussed in the later chapters and their impact on the gross characteristics of the ship evaluated.

3.2 Design Philosophy and Criteria

The primary purpose of this submarine design is to provide a control baseline for the variant submarine designs using electric propulsion. In order for the submarine design to perform this function, each of the designs must be as similar as possible in all other areas of the design. The only changes made in the variants are the installation of the electric drive and the manipulation of the lead and variable ballast loads required to balance the new ship. Therefore the design philosophy is to select a suitably sized propulsion plant and then design a feasible, weight balanced submarine around it.

The principle concern is that all variations have the same shaft horsepower; that is, each variant provides the same steady state power and torque at the same design speed to the

propeller, at design full power operation. This ensures that variations in electrical component efficiency will show up as changes in the overall weight of the propulsion plant in addition to the direct weight effects caused by the new equipments. 25,000 SHP was selected as a reasonable power level for a prototype design.

The validity of the baseline design was verified by comparing the design characteristic indices with the sample values presented in [9].

3.3 Design Procedure.

The basic method requires that an initial weight and gross hull dimensions estimate for the ship be made. The weights are organized in the standard "Ship's Weight Breakdown Summary" (SWBS) which is described in detail in Appendix B The SWBS categorizes every item that will be on the final ship into "weight groups" defined by the function (eg. hull structure, propulsion equipment, outfitting,variable loads and ballast etc) that each group's components provide. Initial weight estimates for the individual weight groups are based on data fits of weight group weight versus some key parameter. For example, the Propulsion Weight Group, Weight Group 2 (W2), is calculated by use of a relationship between plant horsepower and the weight of the plant. Electrical equipment weight, (W3) is estimated using a relation between weight and the expected capacity of the ship's turbine generators.Most designs will have one or two key capabilities that must be accounted for in the initial feasibility planning such as shaft horsepower or ship operating depth which will anchor their initial weight estimates. Once these anchor values are made, the remainder of the weight groups are estimated as percentages of the total ship weight. These percentage estimates are based on successful design data.

The gross dimensions are estimated in a similar manner. Parametric fits are available for floor area, compartment volume and "stackup length" requirements of various critical ship functions. For example, knowing the length of a torpedo, knowing that there must be paths to

load the torpedo from off the ship, load it into the torpedo tube,etc provides a minimum dimension for that function. Considered as a whole, these dimensions provide the initial estimate for the length, diameter,shape coefficients and displaced volume of the ship's hull.

The initial weight estimate must equal the displaced volume weight of the hull. Iteration of the design is required to close the initial solution. For the baseline, shaft horsepower was set at 25,000 HP and electrical generation set at 6 MW (two 3000 KW generators), specifying weight groups 2 and 3. Using these weights to anchor the baseline, the hull parameters were iterated until closure. Finally, the arrangement of the various system components must be such that the submarine will right itself when rolling submerged and can be level trimmed. To achieve these requirements, the longitudinal and vertical centers of gravity (LCG and VCG) of the major weight groups are determined in order to balance the induced moments on the ship. The actual values of the LCG's and VCG's are based upon the actual arrangement of the various components that make of the weight groups. Each piece of equipment is located in the hull, its vertical and longitudinal moments calculated (to some convenient point of reference) and summed to determine the total moments and centers of gravity. For feasibility design studies, these are routinely based upon the "typical position" of the center of gravity from previous designs and then adjusted as required for the individual project.

The results for the mechanical baseline design are summarized in Table 3.1.

Table 3.1 Weight Breakdown Summary

SWBS WEIGHT GROUP	WEIGHT (LTONS)	LCG (FEET)	VCG (FEET)
Hull Structure (W1)	1821.00	142.55	15.23
Propulsion Machinery (W2)	1158.82	165.11	14.11
Electrical Machinery (W3)	206.93	157.59	17.54
Command & Control (W4)	186.24	39.16	18.21
Auxiliary Machinery (W5)	475.94	164.48	16.64
Outfitting (W6)	186.24	109.66	15.87
Weapons Systems (W7)	103.47	65.79	10.53
Condition A1 (Sum W1-W7)	4138.64	144.09	15.24
Lead Ballast	413.86	142.50	13.70
Condition A	4552.50	143.95	15.1
Variable Load Weights	209.53	87.46	9.86
Normal Surfaced Condition	4762.03	141.46	14.87
Main Ballast Tank Weight	619.06	136.08	16.00
Submerged Displacement	5381.09	140.80	15.00
Free Flood	283.22		
Envelope Displacement	5664.31		

The lead ballast serves the dual purpose of ensuring that the submarine will have a tendency to remain upright while submerged (stability lead) and permit modification of the submarine at some later point of its life with equipment that adds weight (margin lead). Submarines that are bodies of revolution have no natural tendency to remain in an upright position. The stability lead is loaded onto the ship such that the lead's vertical center of gravity will force the entire ship's center of gravity to be at least one foot lower than the ship's vertical center of buoyancy. Therefore, when the ship rolls away from the vertical, the separation of the centers of buoyancy and gravity induce a righting moment on the ship to return it to the

upright position. Margin lead is loaded because the amount of buoyancy is fixed by the hull. Weight changes associated with significant changes in equipment can be compensated in weight and in trim moment by adjusting the amount and location of the margin lead. Although simple in concept, the placement of the lead can be difficult and obviously, a design is only feasible if the lead solution is for a location within the ship. The baseline lead solution is summarized in Table 3.2.

Table 3.2 Lead Solution

Lead Category	WEIGHT (LTONS)	LCG (FEET)	VCG (FEET)
Stability Lead:	69.3	141.0	2.0
Margin Lead	344.6	142.8	16.0
Total Lead Ballast:	413.9	142.5	13.70

Speed and powering calculations were made for the basic hull form generated above. The results are summarized in Table 3.3.

Table 3.3 Speed and Powering Summary

Installed Horsepower:	25,000 HP
Maximum Submerged Speed:	32.8 knots
Maximum Surfaced Speed:	20.1 knots

3.4 Submarine Design Based Motor Constraints

As previously discussed, the key constraint that an electric propulsion system and particularly the electric motor must meet is that it must fit in the submarine's hull. The motor will be located as far aft in the pressure hull as possible in order to minimize the amount of

"lost" space used for the propeller drive shaft. Ideally, the shaft would exit the hull at the motor and take up none of the valuable volume inside the hull, but this is unrealistic. The hull diameter near the pressure hull end closure where the motor is located is approximately twenty four feet. Allowing for hull clearance and for structural framing in the vicinity, the outer diameter of the motor and closure should be no more then twenty feet or six meters. The lead solution of the variant design must be feasible. In other words, after installation of the new drive system, the submarine must be longitudinally balanced with the stability lead location within the hull envelope.

3.5 Design Technique Limitations

The model used for these designs is not as sophisticated as techniques available for other types of ship design. The technique provides a data point for each design tradeoff explored. In order to optimize a design, many iterations are required until the designer decides that the value of another iteration is not worth the effort. Without high speed computer synthesis tools, such iterations are labor intensive and time consuming. It is therefore important to realize that the baseline design in no way purports to be the "best" design or even a particularly good design. It is a design which achieved closure when the tests of [9] were applied to it and would be a reasonable early feasibility tradeoff study design. The effects on the design naval architectural indices caused by the electric drive systems will be applicable only within the limited context of early feasibility study.

Chapter Four: Conventional Synchronous Motors

A synchronous motor converts electrical power to mechanical motion by using the interaction of stator and rotor magnetic flux waves. The stator wave is developed on the armature winding; the rotor wave is developed on the field windings. By use of a multiple stator phase windings, the armature flux wave is made to rotate about the stator bore . The rotor flux is induced by a constant (D.C.) current and is constant relative to the rotor. Rotational motion of the rotor is induced as the field flux wave "attempts" to align itself with the rotating stator field.

In synchronous machines, the field flux wave is (to first order) independent of the field on the stator. Therefore, the rotor motion induced occurs at a steady state speed dependent only on the construction of the motor (the number of rotor pole pairs) and on the electrical frequency driving the armature flux field. This steady state shaft speed is the so called "synchronous speed" and is independent of the mechanical load on the shaft. Synchronous speed in revolutions per minute (RPM) is determined by multiplying the electrical frequency by 60 (seconds per minute) and dividing by the number of pole pairs on the rotor. That is,

$$\text{Synchronous Speed} = (60 \bullet \text{frequency}) / (\text{pole pairs})$$

Excellent, detailed derivations of the governing equations for synchronous machines are provided in [1] and [13]. A discussion of these derivations as they apply to the design optimizations done in this study and the computer codes used are presented in Appendix C.

4.1 Synchronous Motor Specific Assumptions

The motors in this study will operate at relatively low shaft speeds of anywhere between zero and 720 rpm. (720 rpm is based on 120 rpm shaft speed and a reasonable single reduction gear ratio) For rotational speeds of this magnitude, the effects of pole saliency on the performance of the motor would be of little significance considering the approximate nature of the model used. Therefore, round rotor motors are assumed for simplicity.

4.2 Machine Simulation Description

Synchronous machines with synchronous speeds of 120 and 720 rpm were modeled using one to twenty pole pairs. After each simulation program run, the input data file for the simulation program was modified to change the random number generator seed to the last random used during the previous run in order to "seed" the next run. This serves to more completely span the available ensemble of random numbers in the various calculations. Each synchronous speed /pole pair combination was run four times with four different initial random number seeds. The best effective weight design of those four was the motor design selected for further analysis.

4.2.1 120 RPM Direct Drive Analysis

Efficiency

Full rated load synchronous efficiency increased with pole pairs until the number of pole pairs reached approximately ten pairs. Above ten pole pairs, the efficiency was in the range of 0.95 to 0.965 for the direct drive motors. Off-design point performance was generally poorer for the direct drive design motors than that for the higher speed motor designs. Efficiencies ranged from 30 to 86 percent for 24 rpm and from 92 to 98 percent for 72 rpm. The highly scattered nature of the off-design-point efficiency data is primarily the result of two factors: the noisey nature of a Monte Carlo simulation scheme and the fact that these efficiencies are not controlled in the course of the optimization and calculated after the fact. Since the speed of the submarine is directly proportional to the rotational speed of the shaft, these off-design-point efficiencies indicate how these motor designs would perform at ship speeds other than full rated speed or "flank speed". Additionally, since the overall efficiency of the propulsion plant is the product of the individual components' efficiencies in the total energy conversion process (ie heat generation to ship's kinetic energy), this means that the ship could pay a significant penalty in overall propulsion plant efficiency to operate a lower

speeds, depending on the motor design selected. This would not be a problem if the ship could be assumed to operate at flank speed for the majority of it's operational lifetime, but such an assumption is not valid.

Weight and Volume

Weight and volume increase approximately linearly and at the same rate (with the exception of the 1 pole pair case) from minimums of approximately 61,000 kilograms and 10 cubic meters to over 100,000 kilograms and 33 cubic meters. As the number of poles increase, the radius of the rotor increases to permit the increased windings. However, the increases are slower than is necessary to ensure adequate effective rotor area per pole to generate the required torque output. Therefore, the length of the motor also increases with the number of pole pairs. The best tradeoff of weight/volume versus motor efficiency appears to occur for motor in the eight to twelve pole pair range. Tables 4.1 through 4.4 and Figures 4.1 through 4.4 apply.

4.2.2 720 RPM Gear Reduced Drive Analysis

Efficiency

The efficiencies for the 720 rpm designs were more efficient across the board than for the direct drive designs. Rated speed performance was generally between 96 and 98.5 percent with the optimum performance coming from designs in the four to ten pole pairs design range. Off-design-point performance was also significantly better for the gear reduced motors . However, for operation at 20 percent of rated speed, the efficiencies were still less than 90 percent.

Weight and Volume

The higher speed motors are, as expected, significantly lighter and smaller than the direct drive designs. The necessity to include a reduction gear mitigates this advantage somewhat. Using parametric design tools ([8,14,15]), a reasonable reduction gear for this application would weigh approximately 40 LT (40,700 kilograms) and be approximately three to four meters in diameter and one meter in length. If one includes consideration for coupling the reduction gear to the shaft, the additional length, in excess of the motor's envelope length can be conservatively estimated to be one and a half meters, making the dimensional impacts of the two basic motor designs (direct drive and gear reduced) roughly equivalent. Tables 4.5 through 4.8 and Figures 4.5 through 4.8 apply.

Table 4.1 120 RPM Synchronous Motor Data
25,000 HP

Number of Pole-Pairs	1	2	3	4	5
Motor Size and Weight					
Envelope Diameter (m)	1.37	1.52	1.57	1.74	1.74
Envelope Length (m)	9.07	5.49	5.35	5.08	5.35
Rotor Radius (m)	0.30	0.44	0.54	0.65	0.69
Rotor Effective Length (m)	7.46	3.48	3.05	2.35	2.50
Back Iron Thickness (m)	0.18	0.13	0.10	0.09	0.08
Stator Bar Depth (m)	0.11	0.13	0.10	0.09	0.08
Rotor Bar Depth (m)	0.13	0.02	0.03	0.03	0.01
Total Volume (m^3)	14.76	10.91	11.40	13.34	14.03
Total Weight (kg)	100,119	64,318	61,431	61,035	62,800
Current Densities (A/m^2)					
Rated Stator Density	1.20E+07	1.20E+07	1.20E+07	1.20E+07	1.20E+07
Rated Rotor Density	3.44E+06	1.34E+07	1.50E+07	1.50E+07	1.40E+07
No Load Rotor Density	1.27E+06	4.93E+06	5.52E+06	6.22E+06	5.57E+06
Loss Terms (watts)					
Hysteresis Losses	4,568	6,673	10,222	13.974	18,522
Eddy Current Losses	80	230	528	962	1,593
Copper Losses	1,862,993	1,577,612	1,248,7551	1,093,328	943,144
Per-Unit Electric Parameters					
Synchronous Reactance (xs)	1.989	1.996	1.999	1.676	1.774
Armature Induced EMF (eaf)	2.709	2.717	2.719	2.413	2.505
Efficiencies					
24 RPM	0.857	0.689	0.737	0.721	0.769
48 RPM	0.962	0.914	0.930	0.929	0.942
72 RPM	0.966	0.948	0.958	0.960	0.967
96 RPM	0.946	0.944	0.955	0.960	0.965
120 RPM	0.909	0.922	0.937	0.944	0.951

Table 4.2 120 RPM Synchronous Motor Data 25,000 HP

Number of Pole-Pairs	6	7	8	9	10
Motor Size and Weight					
Envelope Diameter (m)	1.73	1.89	1.91	1.85	2.13
Envelope Length (m)	5.71	5.75	5.83	6.12	5.84
Rotor Radius (m)	0.70	0.76	0.81	0.81	0.94
Rotor Effective Length (m)	2.81	2.49	2.49	2.83	2.01
Back Iron Thickness (m)	0.07	0.06	0.06	0.05	0.05
Stator Bar Depth (m)	0.07	0.06	0.06	0.05	0.05
Rotor Bar Depth (m)	0.02	0.03	0.02	0.01	0.05
Total Volume (m^3)	14.72	17.65	18.32	18.15	22.94
Total Weight (kg)	65,945	67,284	70,899	74,345	74,881
Current Densities (A/m^2)					
Rated Stator Density	1.20E+07	1.20E+07	1.20E+07	1.20E+07	1.20E+07
Rated Rotor Density	1.35E+07	1.50E+07	1.45E+07	1.48E+07	4.54E+06
No Load Rotor Density	6.40E+06	1.09E+07	8.46E+06	7.71E+06	2.55E+06
Loss Terms (watts)					
Hysteresis Losses	23,801	28,313	35,124	41,968	45,581
Eddy Current Losses	2,457	3,409	4,834	6,498	7,841
Copper Losses	874,380	966,598	793,773	745,435	594,634
Per-Unit Electric Parameters					
Synchronous Reactance (xs)	1.355	0.516	0.913	1.145	0.989
Armature Induced EMF (eaf)	2.112	1.373	1.712	1.919	1.779
Efficiencies					
24 RPM	0.730	0.448	0.642	0.700	0.839
48 RPM	0.935	0.846	0.914	0.927	0.963
72 RPM	0.966	0.935	0.959	0.964	0.979
96 RPM	0.966	0.954	0.966	0.968	0.977
120 RPM	0.954	0.949	0.957	0.959	0.966

Table 4.3 120 RPM Synchronous Motor Data
25,000 HP

Number of Pole-Pairs	11	12	13	14	15
Motor Size and Weight					
Envelope Diameter (m)	6.10	6.09	6.38	6.41	6.40
Envelope Length (m)	2.05	2.20	2.16	2.16	2.28
Rotor Radius (m)	0.91	0.99	0.96	0.99	1.05
Rotor Effective Length (m)	2.39	2.07	2.41	2.43	2.17
Back Iron Thickness (m)	0.05	0.05	0.04	0.04	0.04
Stator Bar Depth (m)	0.05	0.05	0.04	0.04	0.04
Rotor Bar Depth (m)	0.01	0.01	0.02	0.09	0.01
Total Volume (m^3)	22.21	25.43	25.66	25.80	28.64
Total Weight (kg)	77,917	78,988	83,295	87,336	87,325
Current Densities (A/m^2)					
Rated Stator Density	1.20E+07	1.20E+07	1.20E+07	1.20E+07	1.20E+07
Rated Rotor Density	1.50E+07	1.50E+07	1.20E+07	2.98E+06	1.43E+07
No Load Rotor Density	8.58E+06	9.33E+06	9.80E+06	1.59E+06	6.74E+06
Loss Terms (watts)					
Hysteresis Losses	54,595	60,676	68,241	75,782	85,429
Eddy Current Losses	10,331	12,525	15,261	18,251	22,044
Copper Losses	683,388	665,124	737,805	502,204	560,885
Per-Unit Electric Parameters					
Synchronous Reactance (xs)	0.956	0.794	0.324	1.094	1.369
Armature Induced EMF (eaf)	1.749	1.607	1.222	1.873	2.125
Efficiencies					
24 RPM	0.667	0.627	0.443	0.855	0.747
48 RPM	0.919	0.908	0.844	0.962	0.933
72 RPM	0.961	0.958	0.936	0.978	0.966
96 RPM	0.968	0.967	0.958	0.978	0.971
120 RPM	0.961	0.961	0.958	0.969	0.965

Table 4.4 120 RPM Synchronous Motor Data 25,000 HP

Number of Pole-Pairs	16	17	18	19	20
Motor Size and Weight					
Envelope Diameter (m)	2.22	2.21	2.14	2.26	2.32
Envelope Length (m)	6.60	6.92	7.08	6.97	7.04
Rotor Radius (m)	1.03	1.00	0.99	1.05	1.08
Rotor Effective Length (m)	2.45	2.77	3.05	2.72	2.66
Back Iron Thickness (m)	0.04	0.03	0.03	0.03	0.03
Stator Bar Depth (m)	0.04	0.03	0.03	0.03	0.03
Rotor Bar Depth (m)	0.04	0.04	0.02	0.10	0.02
Total Volume (m^3)	28.16	29.27	28.07	30.64	32.66
Total Weight (kg)	93,026	96,170	101,590	103,059	103,632
Current Densities (A/m^2)					
Rated Stator Density	1.20E+07	1.20E+07	1.20E+07	1.20E+07	1.20E+07
Rated Rotor Density	2.23E+06	1.40E+07	1.26E+07	2.61E+06	1.50E+07
No Load Rotor Density	1.06E+06	1.24E+07	9.37E+06	1.66E+06	1.24E+07
Loss Terms (watts)					
Hysteresis Losses	92,477	104,254	119,367	122,887	135,647
Eddy Current Losses	25,454	30,489	36,962	40,166	46,670
Copper Losses	466,874	855,601	609,750	451,036	677,909
Per-Unit Electric Parameters					
Synchronous Reactance (xs)	1.333	0.189	0.484	0.751	0.303
Armature Induced EMF (eaf)	2.092	1.123	1.347	1.570	1.207
Efficiencies					
24 RPM	0.858	0.296	0.543	0.798	0.403
48 RPM	0.960	0.751	0.876	0.944	0.816
72 RPM	0.977	0.898	0.945	0.970	0.922
96 RPM	0.977	0.940	0.962	0.974	0.951
120 RPM	0.970	0.950	0.961	0.968	0.956

Figure 4.1: 120 RPM SYNCHRONOUS MOTOR EFFICIENCY
25,000 HP

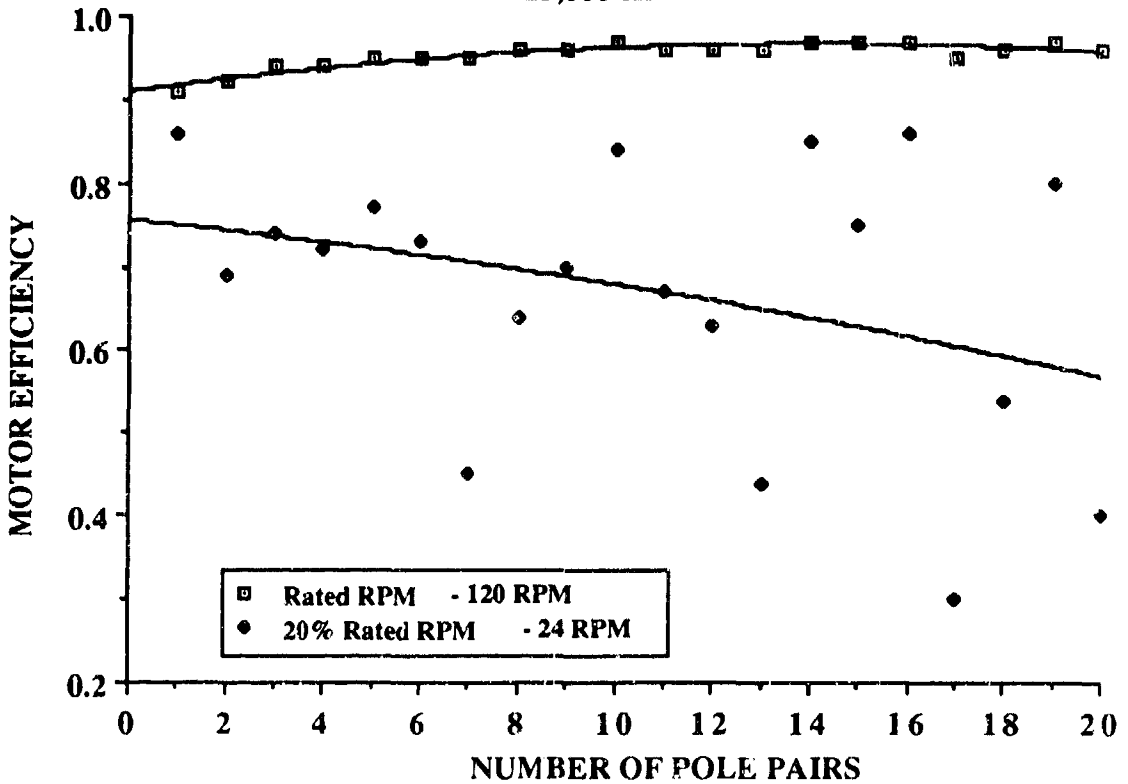


Figure 4.2: 120 RPM SYNCHRONOUS MOTOR EFFICIENCY

25,000 HP

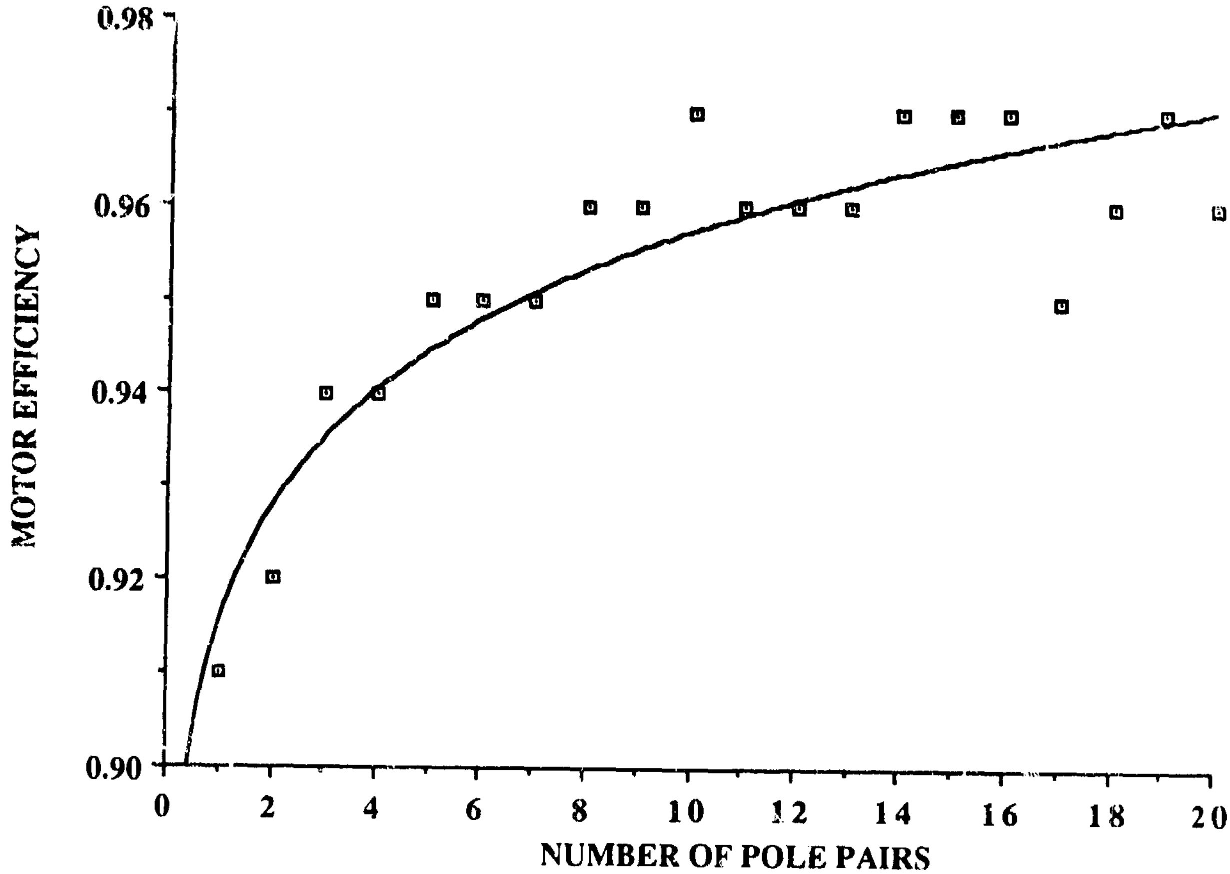


Figure 4.3: 120 RPM SYNCHRONOUS MOTOR WEIGHT
(Kilograms)

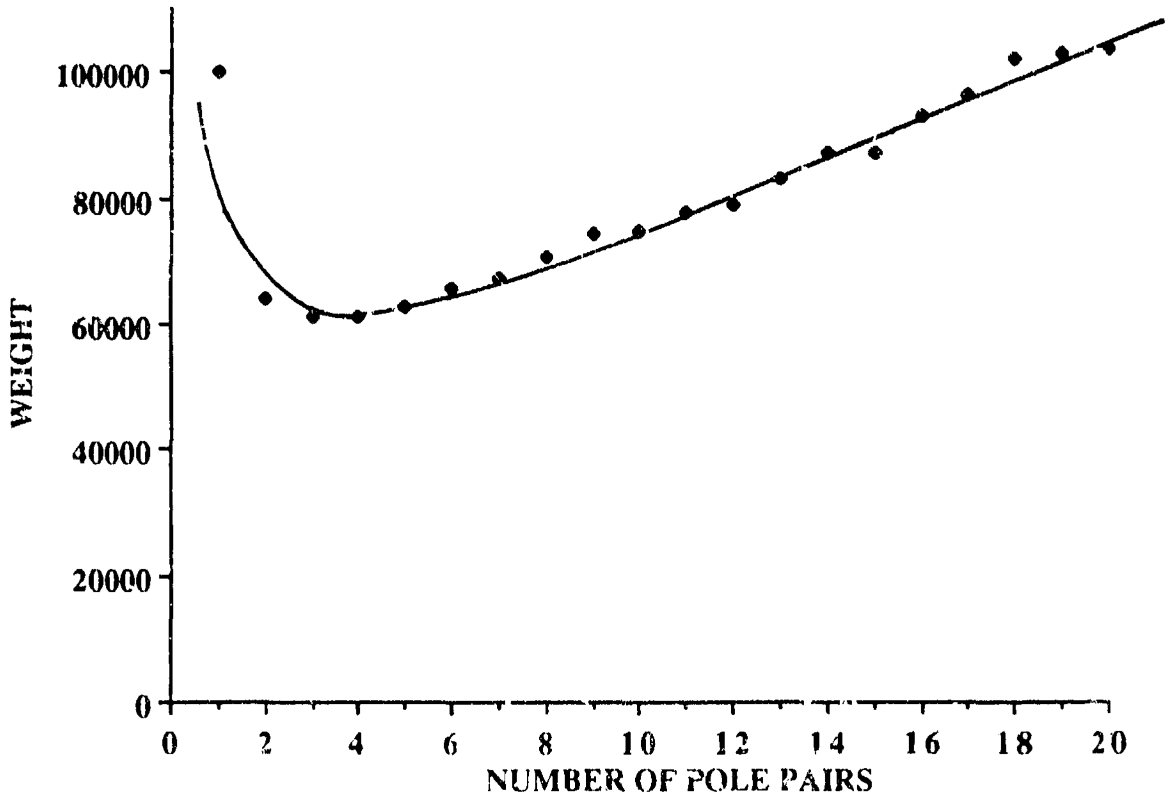


Figure 4.4: 120 RPM SYNCHRONOUS MOTOR VOLUME

(Cubic Meters)

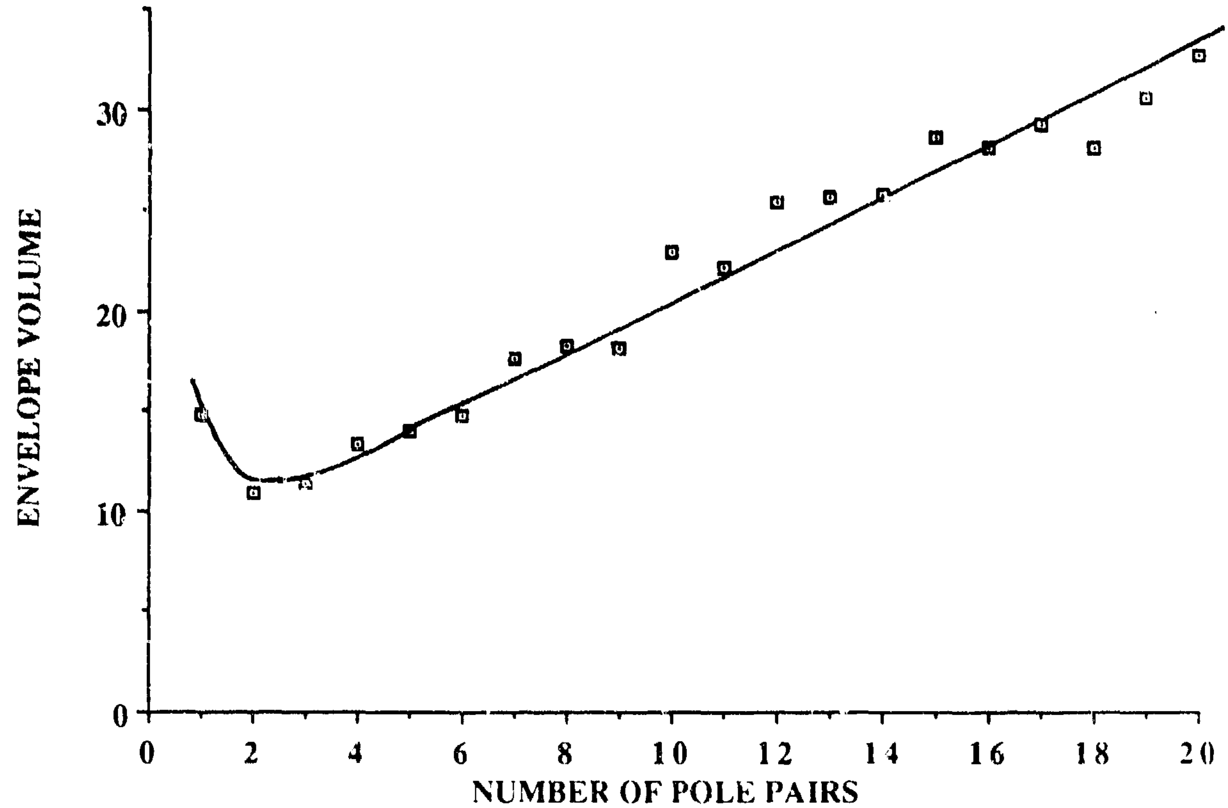


Table 4.5 720 RPM Synchronous Motor Data 25,000 HP

Number of Pole-Pairs	1	2	3	4	5
Motor Size and Weight					
Envelope Diameter (m)	1.01	0.95	1.01	1.03	1.02
Envelope Length (m)	3.74	3.52	3.31	3.47	3.82
Rotor Radius (m)	.20	0.28	0.35	0.39	0.40
Rotor Effective Length (m)	2.65	2.28	1.84	1.86	2.14
Back Iron Thickness (m)	0.12	0.08	0.07	0.06	0.05
Stator Bar Depth (m)	0.12	0.08	0.07	0.06	0.05
Rotor Bar Depth (m)	0.11	0.02	0.02	0.01	0.01
Total Volume (m^3)	3.28	2.74	2.92	3.19	3.46
Total Weight (kg)	21,840	16,738	15,903	16,109	16,882
Current Densities (A/m^2)					
Rated Stator Density	1.19E+07	1.20E+07	1.20E+07	1.20E+07	1.20E+07
No Load Rotor Density	4.27E+06	6.11E+06	5.46E+06	6.84E+06	1.04E+07
Rated Rotor Density	1.15E+07	1.50E+07	1.46E+07	1.41E+07	1.49E+07
Loss Terms (watts)					
Hysteresis Losses	6,097	10,543	15,864	22,131	29,369
Eddy Current Losses	629	2,177	4,912	9,137	15,157
Copper Losses	651,564	412,085	321,420	282,704	291,013
Per-Unit Electric Parameters					
Synchronous Reactance (xs)	1.960	1.720	1.954	1.306	0.581
Armature Induced EMF (eaf)	2.682	2.454	2.676	2.067	1.426
Efficiencies					
144 RPM	0.848	0.868	0.901	0.868	0.736
288 RPM	0.964	0.980	0.977	0.971	0.945
432 RPM	0.979	0.984	0.987	0.985	0.977
576 RPM	0.976	0.984	0.987	0.987	0.984
720 RPM	0.966	0.978	0.982	0.983	0.982

Table 4.6 720 RPM Synchronous Motor Data 25,000 HP

Number of Pole-Pairs	6	7	8	9	10
Motor Size and Weight					
Envelope Diameter (m)	1.13	1.13	1.12	1.29	1.29
Envelope Length (m)	3.53	3.73	4.08	3.67	3.80
Rotor Radius (m)	0.47	0.48	0.47	0.56	0.57
Rotor Effective Length (m)	1.63	1.78	2.10	1.40	1.48
Back Iron Thickness (m)	0.05	0.04	0.03	0.04	0.03
Stator Bar Depth (m)	0.05	0.04	0.03	0.04	0.03
Rotor Bar Depth (m)	0.01	0.04	0.02	0.03	0.01
Total Volume (m^3)	3.91	4.13	4.44	5.24	5.50
Total Weight (kg)	17,024	18,006	19,115	19,108	19,564
Current Densities (A/m^2)					
Rated Stator Density	1.20E+07	1.20E+07	1.20E+07	1.20E+07	1.20E+07
No Load Rotor Density	6.73E+06	4.53E+06	1.01E+07	1.27E+06	9.35E+06
Rated Rotor Density	1.39E+07	8.26E+06	1.20E+07	3.01E+06	1.50E+07
Loss Terms (watts)					
Hysteresis Losses	36,889	45,478	54,317	61,292	74,070
Eddy Current Losses	22,845	32,859	44,851	56,937	76,452
Copper Losses	227,678	198,221	263,438	156,974	190,019
Per-Unit Electric Parameters					
Synchronous Reactance (xs)	1.310	1.036	0.272	1.626	0.790
Armature Induced EMF (eaf)	2.071	1.822	1.184	2.365	1.604
Efficiencies					
144 RPM	0.870	0.878	0.637	0.901	0.790
288 RPM	0.969	0.970	0.918	0.970	0.945
432 RPM	0.984	0.984	0.967	0.983	0.973
576 RPM	0.987	0.987	0.979	0.987	0.981
720 RPM	0.985	0.985	0.981	0.985	0.982

Table 4.7 720 RPM Synchronous Motor Data
25,000 HP

Number of Pole-Pairs	11	12	13	14	15
Motor Size and Weight					
Envelope Diameter (m)	1.38	1.31	1.43	1.41	1.39
Envelope Length (m)	3.82	4.02	3.96	4.07	4.18
Rotor Radius (m)	0.61	0.59	0.65	0.64	0.64
Rotor Effective Length (m)	1.32	1.63	1.34	1.47	1.59
Back Iron Thickness (m)	0.03	0.03	0.03	0.03	0.02
Stator Bar Depth (m)	0.03	0.03	0.03	0.03	0.02
Rotor Bar Depth (m)	0.03	0.02	0.02	0.01	0.01
Total Volume (m^3)	6.30	5.98	7.00	6.96	6.99
Total Weight (kg)	19,971	21,282	21,321	22,321	23,379
Current Densities (A/m^2)					
Rated Stator Density	1.20E+07	1.20E+07	1.20E+07	1.20E+07	1.20E+07
No Load Rotor Density	1.08E+07	1.06E+07	1.15E+07	1.03E+07	9.85E+06
Rated Rotor Density	1.43E+07	1.43E+07	1.50E+07	1.42E+07	1.44E+07
Loss Terms (watts)					
Hysteresis Losses	83,066	97,408	106,287	120,753	136,537
Eddy Current Losses	94,312	120,649	142,618	174,492	211,393
Copper Losses	197,345	190,573	187,939	172,118	163,438
Per-Unit Electric Parameters					
Synchronous Reactance (xs)	0.459	0.478	0.426	0.517	0.626
Armature Induced EMF (eaf)	1.328	1.342	1.301	1.374	1.464
Efficiencies					
144 RPM	0.718	0.715	0.715	0.712	0.718
288 RPM	0.929	0.924	0.924	0.916	0.912
432 RPM	0.967	0.963	0.963	0.958	0.954
576 RPM	0.978	0.975	0.975	0.971	0.968
720 RPM	0.980	0.979	0.977	0.976	0.973

Table 4.8 720 RPM Synchronous Motor Data
25,000 HP

Number of Pole-Pairs	16	17	18	19	20
Motor Size and Weight					
Envelope Diameter (m)	1.50	1.53	1.50	1.50	1.61
Envelope Length (m)	4.30	4.21	4.28	4.37	4.35
Rotor Radius (m)	0.66	0.71	0.70	0.70	0.75
Rotor Effective Length (m)	1.49	1.34	1.47	1.53	1.30
Back Iron Thickness (m)	0.02	0.02	0.02	0.02	0.02
Stator Bar Depth (m)	0.02	0.02	0.02	0.02	0.02
Rotor Bar Depth (m)	0.07	0.01	0.01	0.01	0.02
Total Volume (m^3)	8.38	8.52	8.31	8.53	9.73
Total Weight (kg)	23,707	23,949	25,000	25,969	25,721
Current Densities (A/m^2)					
Rated Stator Density	1.20E+07	1.20E+07	1.20E+07	1.19E+07	1.20E+07
No Load Rotor Density	1.31E+07	1.10E+07	9.72E+06	9.24E+06	1.06E+07
Rated Rotor Density	1.37E+07	1.32E+07	1.50E+07	1.23E+07	1.32E+07
Loss Terms					
Hysteresis Losses	136,812	157,807	177,426	193,796	202,158
Eddy Current Losses	225,940	276,901	329,640	380,057	417,320
Copper Losses	350,699	174,339	147,361	147,881	154,264
Per-Unit Electric Parameters					
Synchronous Reactance (xs)	0.082	0.303	0.720	0.466	0.357
Armature Induced EMF (eaf)	1.051	1.206	1.543	1.333	1.247
Efficiencies					
144 RPM	0.374	0.630	0.690	0.654	0.618
288 RPM	0.794	0.884	0.891	0.877	0.865
432 RPM	0.912	0.941	0.940	0.933	0.927
576 RPM	0.949	0.961	0.959	0.954	0.950
720 RPM	0.963	0.968	0.966	0.963	0.96

Figure 4.5: 720 RPM SYNCHRONOUS MOTOR EFFICIENCY
25,000 HP

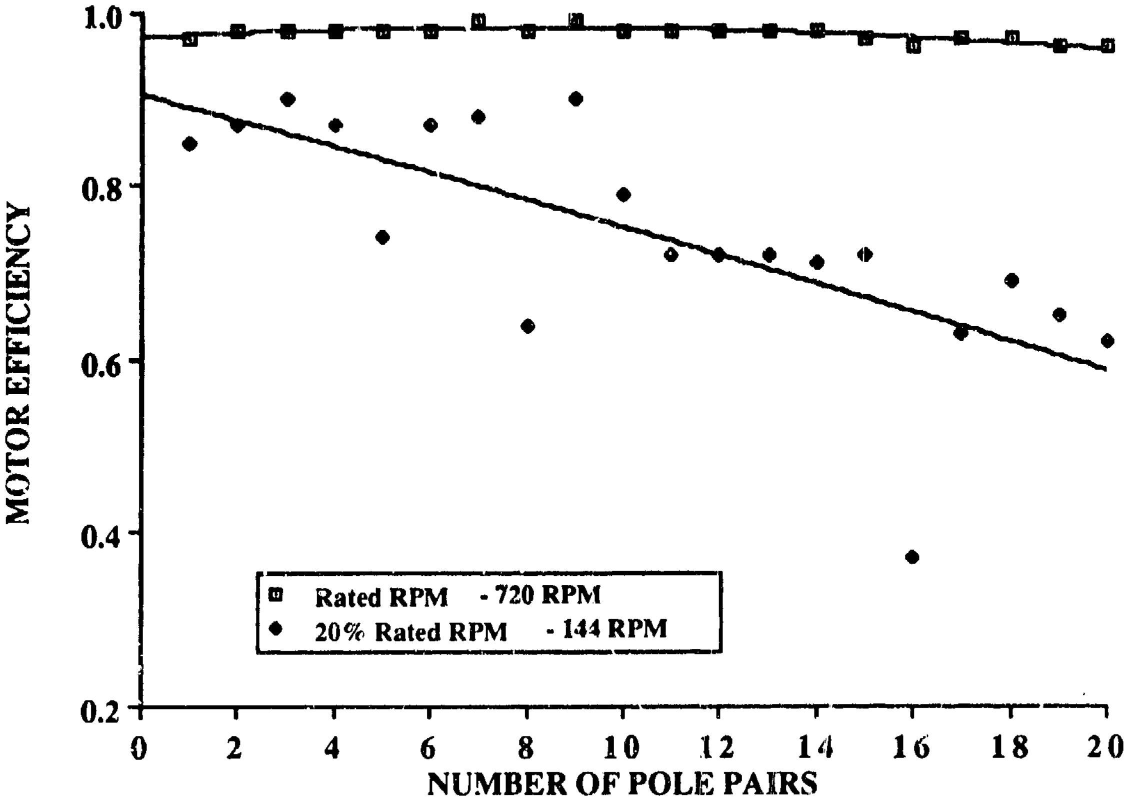
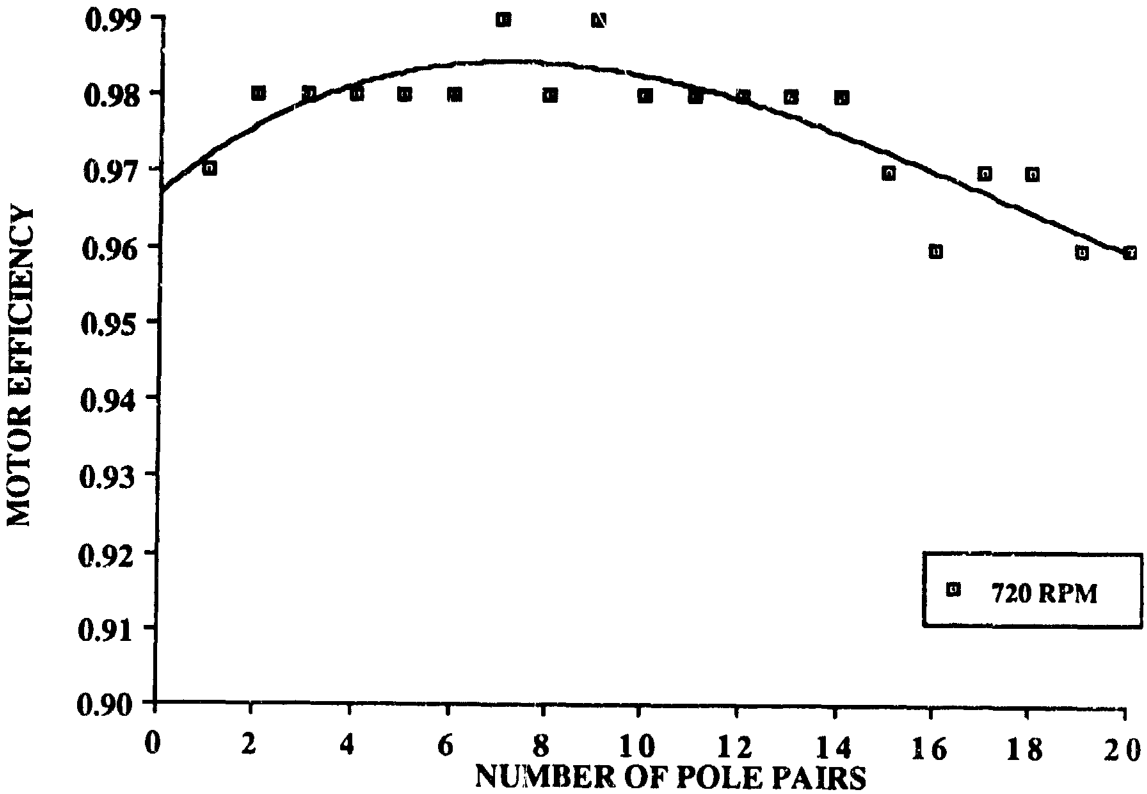


Figure 4.6: 720 RPM SYNCHRONOUS MOTOR EFFICIENCY
25,000 HP



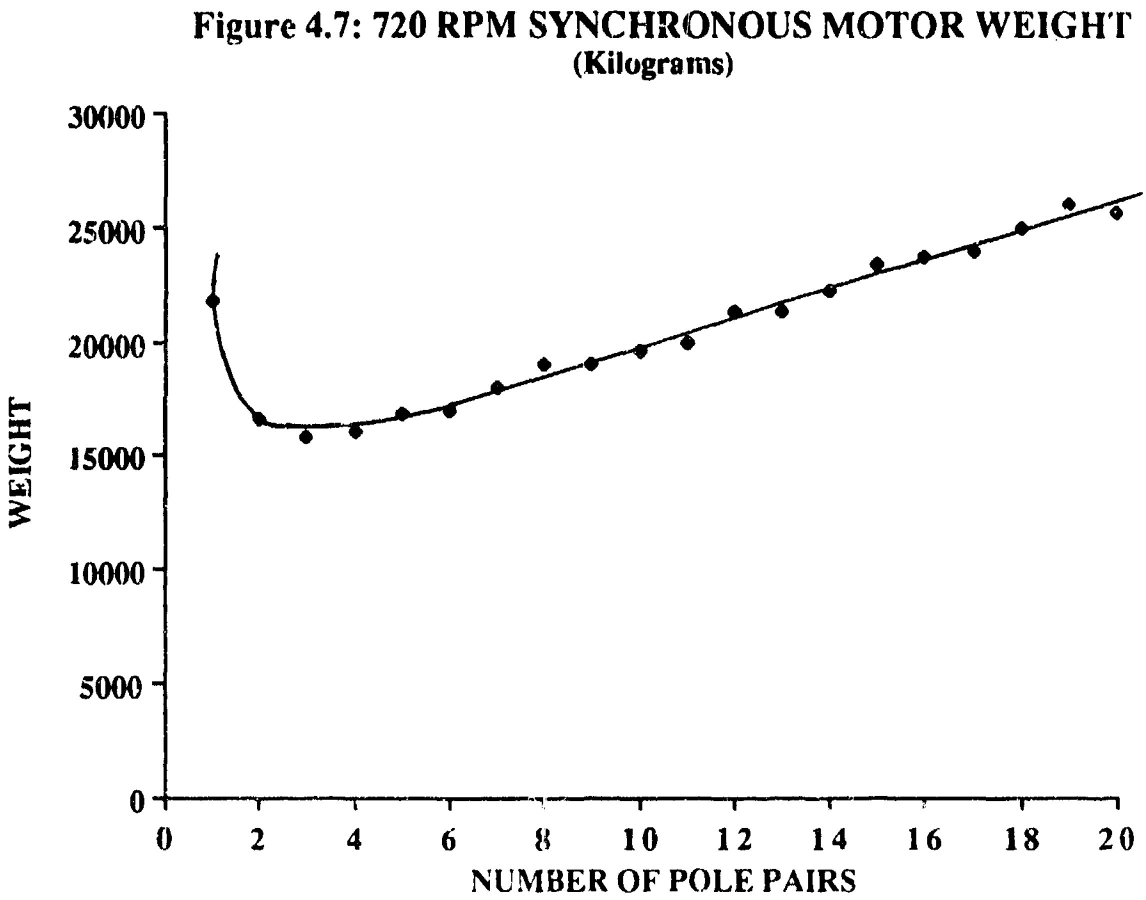
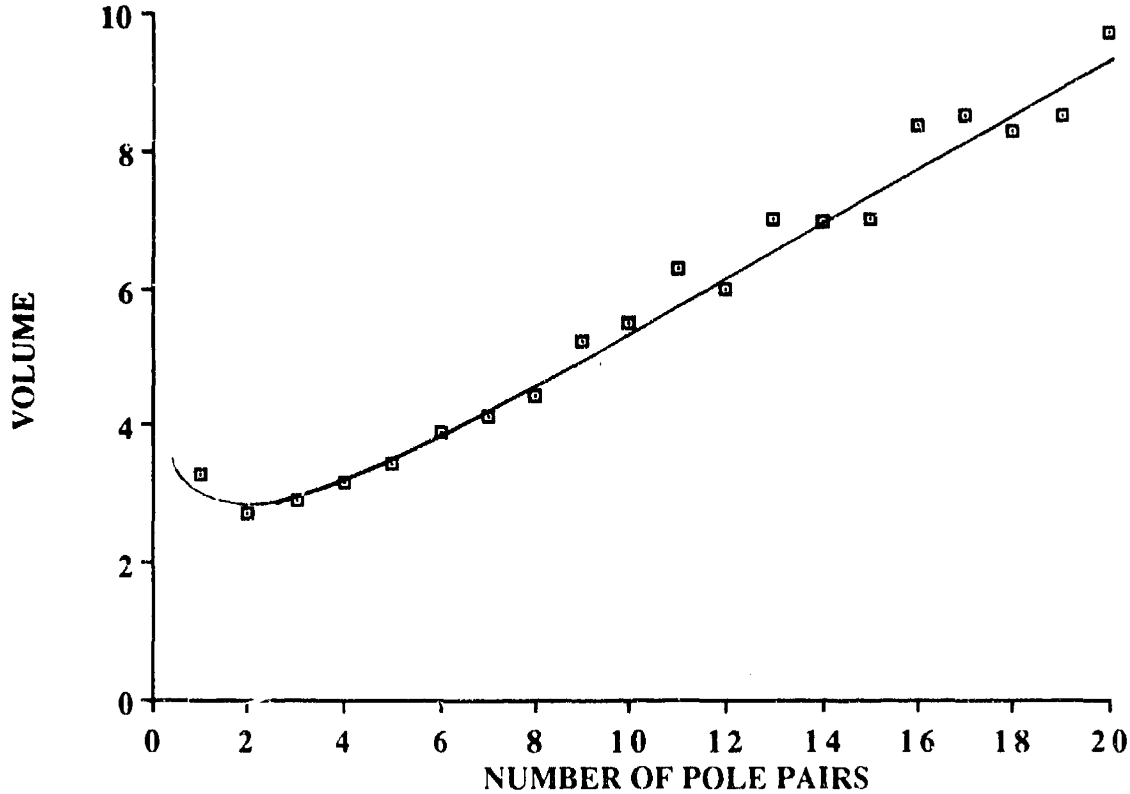


Figure 4.7: 720 RPM SYNCHRONOUS MOTOR WEIGHT
(Kilograms)
WEIGHT
30000
25000
20000
15000
10000
5000
0
0
2
4
6
8
10
12
14
16
18
20
NUMBER OF POLE PAIRS

Figure 4.8: 720 RPM SYNCHRONOUS MOTOR VOLUME
(Cubic Meters)



4.3 Discussion

An unexpected side affect of enforcing a limit on the current density in the rotor bars was the erratic behavior of the off design point efficiency as indicated by the particularly low efficiencies of some of the motors (eg.120 rpm: 7, 13, 17 and 20 pole pairs and 720 rpm: 5, 8 and 16 pole pairs). These low efficiencies tended to occur when the design limits on the rotor current density and the rotor-stator gap width could not be met and the design loop had to reinitialize. The end result of this was that the induced EMF on the armature became lower than was otherwise typical of the other simulations. Since the full load rotor current density is directly proportional to the no load current density with the normalized induced EMF as the constant of proportionality (ie. $J_R = eaf \cdot J_{Rnl}$), the reduction of the eaf term reduced the full load rotor current until its limit was met. The low off-design-point efficiencies occur because the no load current density is not substantially different from the full load current density. Therefore, as output power, stator current and frequency decrease linearly with shaft speed, the current on the rotor is not significantly changing so the losses due to copper resistance on the rotor do not significantly change. For example, consider the 120 rpm, 17 pole pair motor data from Table 4.4 summarized in Table 4.9.

Table 4.9 120 RPM, 17 Pole Pair Motor Efficiency Drivers

Rated Stator Current Density	1.2×10^7 Amp/m^2
eaf	1.123 per unit
No Load Rotor Current Density	9.67×10^6 Amp/m^2
Full Load Rotor Current Density	1.26×10^7 Amp/m^2

Note the extremely low value of the full load eaf which is nearly unity. This a direct result of imposing limitations on the rotor current density. In order to achieve the required reduction in J_R, the optimization converged to a "best" solution with a very low value of eaf. As noted earlier, the eddy current and hysteresis losses and proportional to electrical frequency

which in turn is directly proportional to shaft speed. Stator and rotor copper losses are proportional to the square of the respective current densities so stator losses are proportional to the square of the shaft speed while rotor losses are not. For an eaf value of nearly unity, J_R and therefore the rotor current copper losses are effectively speed independent. When evaluating the off-design-point operation and efficiency, this independence of shaft speed leads to the particularly low efficiencies noted above.

To correct the high degree of scatter in the off-design-point efficiency would require either a different design technique (as opposed to the stochastic Monte Carlo method) or a different type of objective function. The latter technique is discussed in more detail in Chapter Five.

4.4 Random Variable Selection Revisited

Upon reflection, it was noted that the motors with the poorest efficiencies were characterized by the near unity values of eaf and that these values of eaf arose from unacceptably low values of the synchronous reactance, xs. Values of only a few tenths (per unit) are not realistic for practical motor fabrication. However, in limiting the field current density and adjusting the gap width to achieve this limit, certain geometries and electrical configurations resulted in optimization that were driven to these less than useful results.

One method to solve this would be to bound the value of xs below in addition to the limit upon its maximum value currently in the program. This was not done due to time considerations and because the code as currently constructed already takes a long time to run each particular optimization. Adding another constraint , particularly one that is likely to be in the limiting set of constraints on a regular basis could only serve to slow the execution of the code further and might even lead to solution infeasibility .

The set of random variables used to solve the problem was reevaluated. First it was noted that in all but a very few of the total runs of the design program, the stator current density converged to the maximum value permitted by the code. Indeed, in those few cases where the

current density was not the maximum value, only a few tenths of a percent difference existed. Therefore, little advantage in solving the problem accrued in using the stator current as a random variable so the decision was made to fix the stator current density at the limiting value. Secondly, since low values of the synchronous reactance led to the problem, xs was arbitrarily fixed at a value of 2.0 per-unit. The rated load rotor current density was randomized and limited to a maximum value in the same manner that the stator current density had been limited in earlier iterations. Specifying the synchronous reactance specifies the armature induced EMF (eaf) which in turn specifies the no load rotor current density.

This changes the way the problem is solved. Using this method, xs ties the stator current and the randomly generated physical dimensions to the rotor by fixing the value of the motor gap width. Random selection of the rotor current mandates that the rotor bar depth (dr) be calculated rather than randomly selected as previously done. Since the no load rotor current density is a function of both the rotor bar depth and the gap width, ie.

$$\text{jml} = \frac{BR \bullet g \bullet p}{(2\, \mu_0 \bullet r \bullet RSF \bullet k_f \bullet l_r \bullet dr)}$$

where:

BR	=	The radial flux density
g	=	the stator - rotor gap width
r	=	the radius of the rotor
RSF	=	the rotor slot factor or the percent of the rotor slot that is conductor
k_f	=	the rotor winding factor
l_r	=	the rotor slot space factor or the percent of the rotor circumfance that is taken up by slots

Knowing jrnl permits direct calculation of dr and provided the mathematical coupling of the rotor to the stator. The remainder of the optimization process is identical to the earlier iterations.

The new code was implemented along with a scheme which permits the number of iterations in the random variable selection subroutine and the magnitude of the stepsize reduction (for small changes in effective weight) to be specified as input variables in the data file. The concept was to be able to control the size of the object space "searched" by the Monte Carlo random variable selection. This was done in order to make the results of the synthesis more self consistent for similar motor geometries and less sensitive to the noise inherent in the simulation techniques used.

When the modified code was run, the previously seen variation in the rotor current was no longer evident. Although some data scatter still persisted, the full load rotor current density tended to converge to the maximum allowed value, varying between 12.7 and 15.0 Mamperes/m^2. The rotor slot depth varied to compensate for the variation that resulted from the ramdom nature of the rotor slot space factor (l_r) and the full load rotor current density. Otherwise, the design parameters were self consistent among the runs of the new program for both the three and seven pole pair motor designs.

In comparison to the motor designs run under the previous scheme, the physical dimensions of the designs were also consistent with the new code.with the new code machines tending to be slightly larger (3 to 5%) and heavier (2 to 4%).

Efficiency tended to be slightly lower (1to 3%) for both pole pair motor designs synthesized with the new scheme. This was primarily due to the new code converging to a relatively smaller rotor conductor area for the current density to "use" (and resulting higher resistance). This results in the new code generated motors having current losses forty five to fifty five percent higher (at rated load and for comparable rotor current densities) than the previous design scheme machines. The degree of variation in full load efficiency was not

significant given the difference in the approach to optimality. In both the 3 and 7 pole pair cases, however, off-design-point efficiences tended to be higher due to the nearly three fold variation of the rotor no load current density forced by specifying xs as 2.0 per unit.

The following conclusions can be drawn from the analysis of the two design schemes repective output.

1. The physical (dimensional) designs of the two methods are essentially the same, certainly to the level of accuracy needed by a naval architect looking at electric drive as a possibility in early feasibility studies, the weight and size output of both schemes are both "good enough". Since the first scheme takes much less time to run (5 to 8 minutes as opposed to 15 to 25 minutes on a 8 MHz IBM PC compatible computer with floating point coprocessor), it should be considered first when the actual electric parameters of the motor are not yet important.
2. The first scheme produces reasonable output for the electrical parameters of the motor except where the rotor current limit is a problem and iterations on the gap width are required. In this case, the first scheme tends to produce motors with unreasonable values for the synchronous reactance and for the normalized EMF on the armature. However, although the studies here indicate that the physical dimensions of such a motor are still reasonable estimates, the ship designer should default to using the second scheme before a ship feasibility study design becomes too mature with that electric drive option selected.
3. When reasonable estimates for the electric performance of the motor are required, the second scheme should be used. A large number of iterations per random variable selection loop (about 50) and only small changes in the step size (about 75% of current step size) as the solution approaches optimality should be selected. This assures that the results are self consistent among multiple runs of the program for the electrical parameters. Such consistency

would be particularly important when sizing the required generators, estimating the weight of cable runs and determining the size and weight of swtchgear and speed controllers. These decisions might be done simultaneously in different offices, each using a different run of the code, making consistency a must.

Chapter Five: Efficiency Improvement Schemes

5.1 Discussion

As discussed in the previous chapter, the off-design-point efficiency of the motors is a significant driver on the overall ship since the total stored energy that must be loaded onto the ship is not only a function of peak load efficiency. In fact, the actual efficiency of an operational propulsion system may be a function of the motor speed. It will definitely be a function of the manner in which the motor is operated by the users. The energy balance that establishes the ship's endurance requirements must consider:

- Propulsion efficiency as a function of ship speed
- The speed probability density function for the ship's expected operational tempo.
- Required replenishment cycle.

For the sake of illustration, consider a speed probability density function of the form

$$P(\nu) = \begin{cases} 0.1 & \text{if } 0.0 \leq \nu \leq 0.2 \\ 0.2 & \text{if } 0.2 \leq \nu \leq 0.4 \\ 0.4 & \text{if } 0.4 \leq \nu \leq 0.6 \\ 0.2 & \text{if } 0.6 \leq \nu \leq 0.8 \\ 0.1 & \text{if } 0.8 \leq \nu \leq 1.0 \end{cases}$$

where :

$$\nu = \text{speed / rated speed}$$

Two reasonable motor designs from chapter 4 are the 3 and 7 pole pair direct drive motors. The three pole pair motor is the "best" design from the standpoint of the effective weight parameter while the seven pole motor is apparently more efficient for only slightly more

weight. Let the speed averaged motor efficiency be defined as:

$$\eta_{speed} = \int_0 \eta(\nu) P(\nu) \, d\nu$$

for the continuous case or

$$\eta_{speed} = \sum_{i=1}^{n} \eta(\nu_i) P(\nu_i)$$

for the case of a discrete set of speeds of interest. Then, the speed averaged efficiency for the "best" motor is 0.880 while the apparently more efficient motor's speed averaged efficiency is 0.817 (numerically integrated). Therefore, in this case, the off-design-point efficiencies dominate the lifetime performance of the 7 pole pair motor making its performance significantly worse than the "best" motor. Therefore, for the same operational schedule, the 7 pole pair machine would use stored energy approximately six percent faster than the 3 pole pair machine. This translate to a shorter required replenishment period for the 7 pole pair machine (an operational limitation) or an increased Weight Group 2 commitment in the initial design of the submarine to offset the difference.

The submarine designer tries to minimize the weight of the submarine consistent with the requirements laid against the design by the prospective customer. Therefore, methods to enhance the off-design-point efficiencies (and therefore the speed averaged efficiency) of the motor designs should be investigated.

5.2 Armature Voltage Control Efficiency Enhancement

As discussed in Chapter 4, the lower off-design-point efficiencies resulted from the imposition of limits on the rotor bar current densities. In these cases, the simulations resulted in values of normalized EMF on the armature (eaf) very close to one per unit. For these cases, the rotor current and rotor current losses do not significantly change with power output. The

equation relating eaf to the terminal voltage and armature current (per unit) is:

$$eaf^2 = v_t^2 + (x_s i)^2 + 2i\, x_s \sin \psi$$

where:

eaf	=	per unit induced EMF on the armature
v_t	=	per unit terminal voltage on the armature
i	=	per unit armature current
x_s	=	per unit synchronous reactance on the armature
ψ	=	power factor angle

Under normal rated operation, the terminal voltage and the armature current per unit values are unity. The synchronous reactance is specified by the design of the machine. The power factor is specified by the design of the total system including the generators and motor/generator field currents. Thus eaf is a function only of the synchronous reactance for rated operation. For off-design-point operation with constant terminal voltage, the only variable is the current on the rotor. From the above equation it is apparent that for typical motor applications ($\sin \psi \geq 0$), the minimum value of eaf is the normalized terminal voltage. This would routinely correspond to the no load ($i = 0$) condition.

In order to improve off-design-point efficiency, the goal is to reduce the current on the rotor where:

$$J_R = eaf \cdot J_{Rnl}$$

The no load rotor current density is set by the design of the motor so that the only way to reduce the loaded rotor current density is to reduce eaf. An obvious method to do this is to attempt a "voltage-power" controller system that sets the input voltage to the armature as a function of output power setting.

5.3 Analysis Method

The computer program used to analyze the efficiency of the synchronous motors was modified to generate efficiency as a function of v_t. Maximum available power (P) for a given value of v_t is directly proportional to v_t since

$$P = 3 | V \bullet I | \bullet v_t.$$

and the armature current is limited to the full load value because of the heat removal capacity designed into the stator bars. The output of the program is a series of "iso-voltage" efficiency versus power curves. Figures 5.1 and 5.2 are derived from the program output for the three and seven pole pair examples discussed above.

Figure 5.1: ELECTRIC EFFICIENCY VERSUS SHAFT RPM

3 POLE PAIR MOTOR

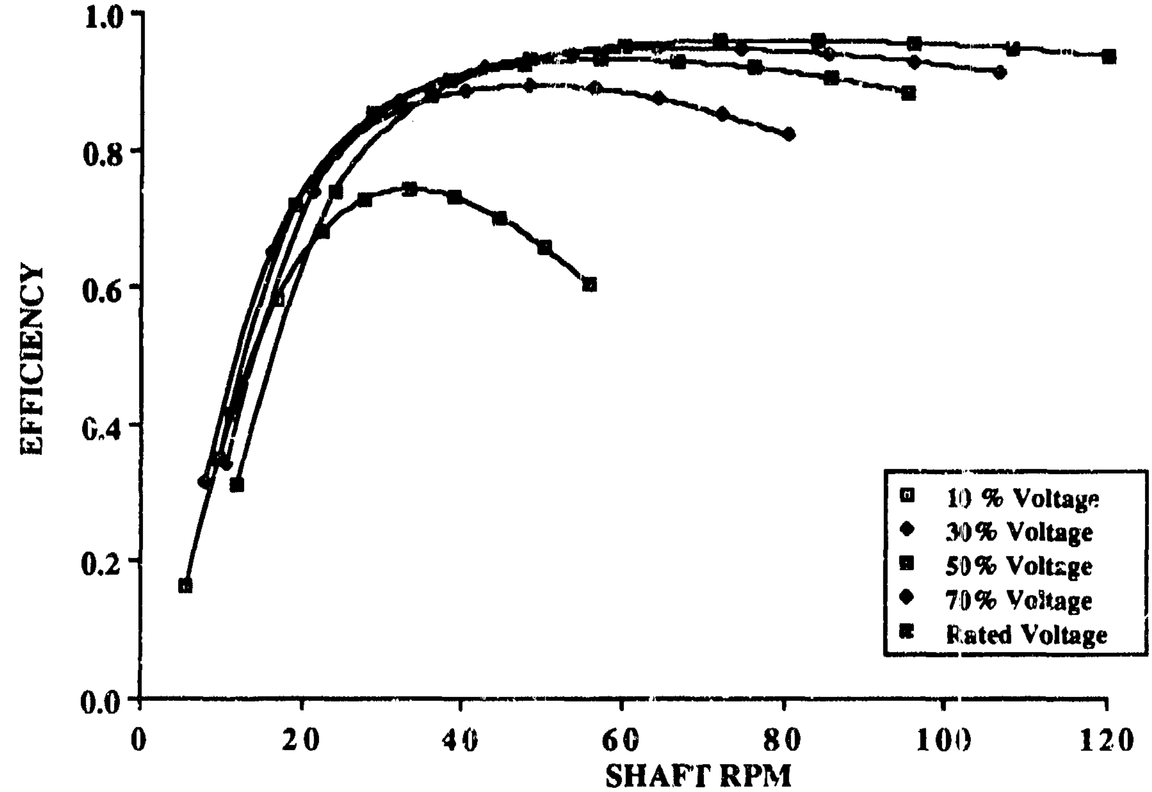
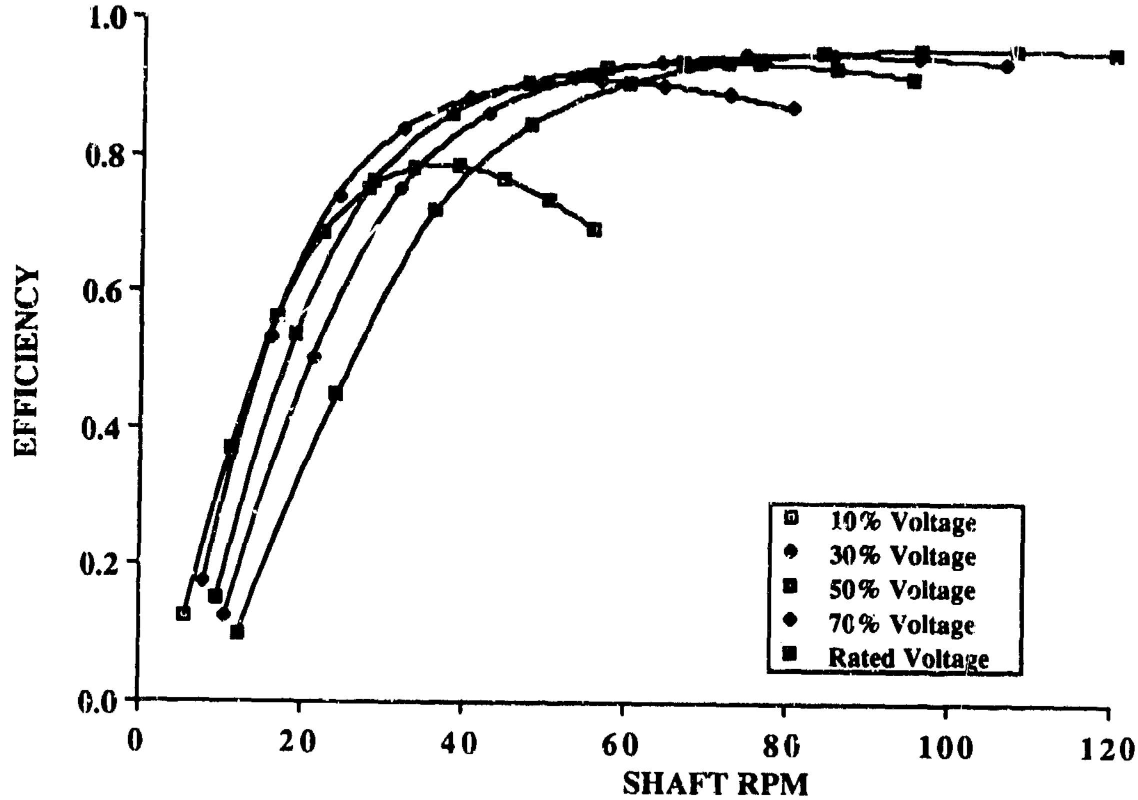


Figure 5.2: ELECTRIC EFFICIENCY VERSUS SHAFT RPM
7 POLE PAIR MOTOR



A simplistic method of programming the control system is to set the voltage with the maximum efficiency for a given power setting. Figures 5.3 and 5.4 show the impact of such program when compared to the performance of the motor when operated only at the rated voltage.

Figure 5.3: ELECTRIC EFFICIENCY VERSUS SHAFT RPM

3 POLE PAIR MOTOR

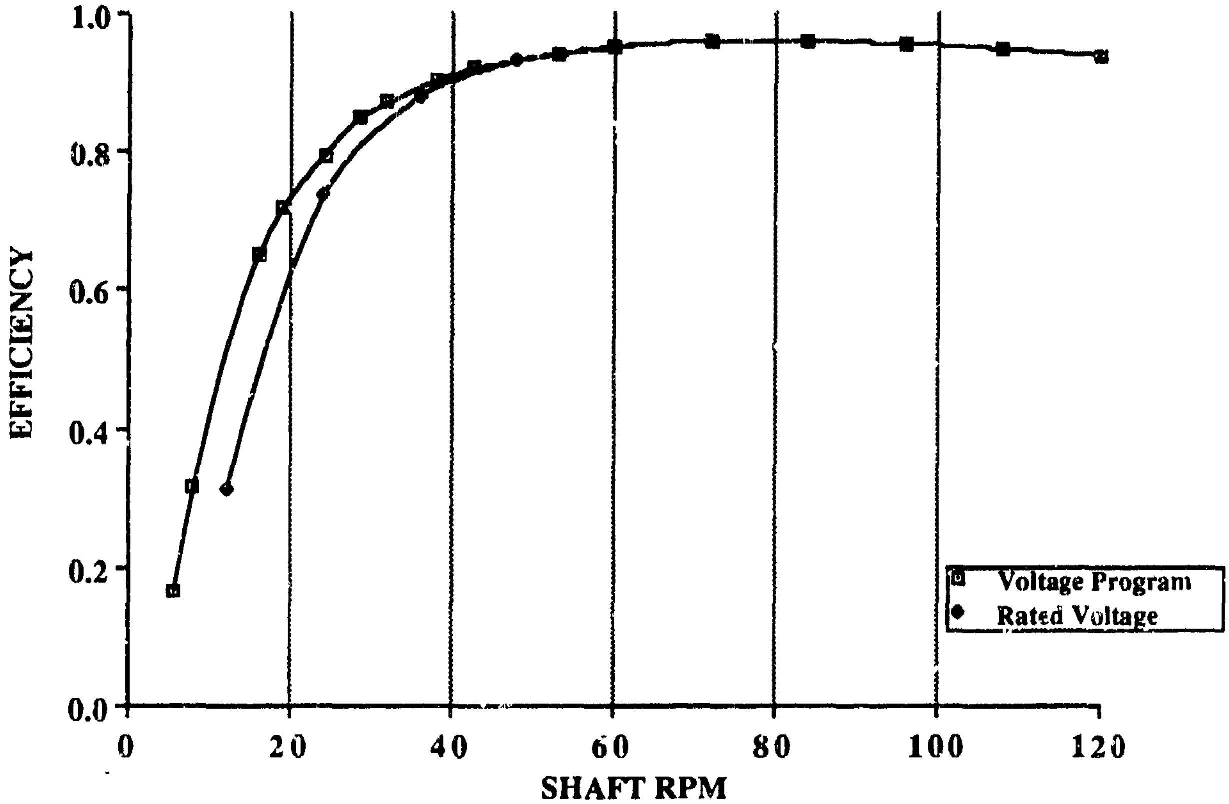
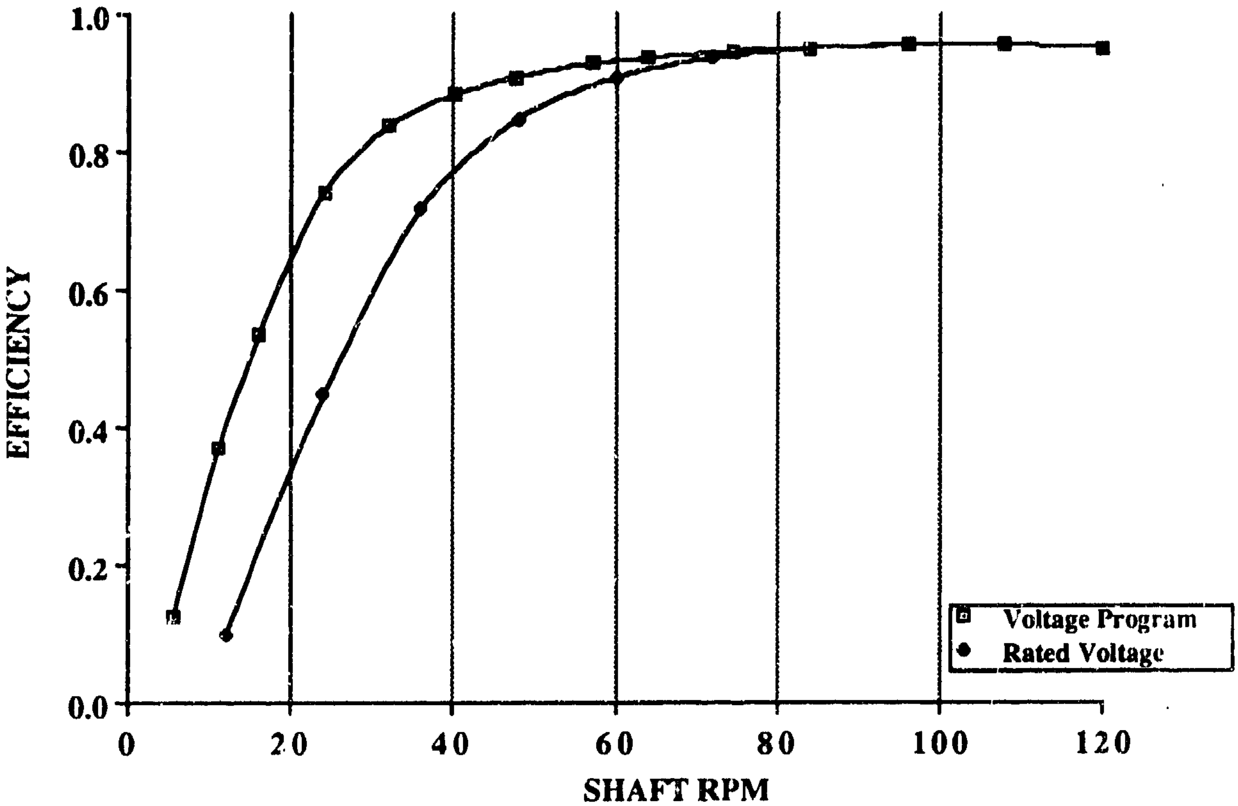


Figure 5.4: ELECTRIC EFFICIENCY VERSUS SHAFT RPM

7 POLE PAIR MOTOR



The result of the study is that the performance of the motor designs can be improved by use of a voltage programing efficiency enhancement technique but that the magnitude of the improvement varies. In the case of the 3 pole pair design, the technique only yields a speed averaged efficiency of 0.89. This is because the rotor current density for the 3 pole pair motor already varies by almost a factor of three between the no load and full load case so the rated voltage variation is sufficient to reduce the rotor current copper losses. In other words, power drops by a factor of 10 (100% to 10%), rotor current losses drop by nearly a factor of 10 also (3 to the second power). Thus any further reductions in J_R associated with reduction in eaf are not as significant as the same changes are in the 7 pole pair motor case. For that motor design,

the voltage program achieves a speed averaged efficiency of 0.877, or nearly that of the unprogrammed 3 pole pair motor. In this case, where originally the rotor current varied only by a factor of 1.3, the reduction of the eaf by the voltage program improved the off-design-point efficiency of the motor by a factor of almost two for motor speeds between 20 and 40 RPM and by four to ten percent in the heavily used 40 to 80 RPM speed range.

5.4 Power Factor Efficiency Enhancement

Since the eaf for most motors is between 1.0 and 3.0, another method to improve the efficiency might be to reduce the current total load on the machine by reducing the apparent power (volt-amperes). By means of a power factor closer to unity than the standard 0.8 power factor used in the initial code, the concept is to reduce the total amperes (and therefore the associated losses) by reducing the total reactive power. In this manner, the system consisting of the motor and the driving generator are operated at the best possible efficiency.

5.5 Analysis Method

The computer program was modified for a power factor of 1.0 and was run five times each for 120 RPM, three and seven pole pair motor designs. The results were tabulated and compared to all previous synthesis runs for those motor designs (with 0.8 power factors). Tables 5.1 and 5.2 apply.

Table 5.1 3 Pole Pair Motor Efficiency Comparison

PARAMETER	PF = 1.0	PF= 0.8
Motor Size and Weight		
Envelope Diameter (m)	1.40 - 1.50	1.53 - 1.64
Envelope Length (m)	5.04 - 5.49	5.35-5.99
Rotor Radius (m)	0.48 - 0.51	0.49-0.54
Stator Bar Depth (m)	0.09 - 0.10	0.09-0.10
Rotor Bar Depth (m)	0.03 - 0.15	0.03-0.21
Total Volume (m^3)	9.26 - 9.84	11.40-12.66
Total Weight (metric tons)	52.6 - 54.3	61.4-65.9
Current Densities (MegaAmperes/m^2)		
Rated Stator Density	12.0	12.0
Rated Rotor Density	2.4- - 44.6	2.9-15.0
No Load Rotor Density	1.4 - 5.5	1.7-8.6
Loss Terms (Kilowatts)		
Hysteresis Losses	7.7 - 8.8	8.4-10.2
Eddy Current Losses	0.4 - 0.5	0.4-0.5
Copper Losses	903 - 986	1,144-1,420
Per-Unit Electric Parameters		
Synchronous Reactance (xs)	1.244 - 1.867	0.854-1.999
Armature Induced EMF (eaf)	1.596 - 2.118	1.659-2.719
Efficiencies		
24 RPM	0.805 - 0.928	0.503-0.816
48 RPM	0.960 - 0.984	0.861-0.962
72 RPM	0.974 - 0.984	0.933-0.975
96 RPM	0.967 - 0.974	0 .943-0.964
120 RPM	0.949 - 0.953	0.929-0.942
Speed Averaged	0.952	0.974

Table 5.2 7 Pole Pair Motor Efficiency Comparison

PARAMETER	PF = 1.0	PF= 0.8
Motor Size and Weight		
Envelope Diameter (m)	1.55 - 1.80	1.84-2.02
Envelope Length (m)	5.03 - 6.08	5.47-5.75
Rotor Radius (m)	0.64 - 0.74	0.76-0.83
Stator Bar Depth (m)	0.05 - 0.06	0.06-0.07
Rotor Bar Depth (m)	0.01 - 0.05	0.03-0.08
Total Volume (m^3)	12.46 - 14.90	16.52-19.33
Total Weight (metric tons)	56.6 - 60.3	66.8-68.6
Current Densities (MegaAmperes/m^2)		
Rated Stator Density	12.0	12.0
Rated Rotor Density	7.2 - 15.0	3.7-15.0
No Load Rotor Density	6.5 - 14.0	1.4-10.9
Loss Terms (Kilowatts)		
Hysteresis Losses	24.0-26.1	27.7-28.3
Eddy Current Losses	2.9 - 3.1	3.3-3.4
Copper Losses	684 - 849	690-967
Per-Unit Electric Parameters		
Synchronous Reactance (xs)	0.377 - 1.411	0.516-1.852
Armature Induced EMF (eaf)	1.069 - 1.730	1.373-2.579
Efficiencies		
24 RPM	0.378 - 0.766	0.448-0.913
48 RPM	0.823 - 0.924	0.846-0.978
72 RPM	0.932 - 0.967	0.935-0.984
96 RPM	0.957 - 0.971	0.954-0.977
120 RPM	0.955 - 0.963	0.949-0.963
Speed Averaged	0.862 - 0.948	0.918

In general, the 1.0 motors have smaller rotor lengths and diameters. This corresponds to motor weights 11 to 17 percent lower than the 0.8 power factor designs. However, the off-design-point efficiencies of the alternative motors are not consistently better than the values for the motors synthesized with power factors of 0.8.

For the three pole pair motors, the 1.0 power factor efficiencies are better across the board. For these machines, the higher power factor machines copper losses are 15 to 25 percent lower than the 0.8 power factor machines, improving the rated load efficiencies. The values of eaf,however,are still high enough to sufficiently reduce the field current loss terms as motor speed lowers. Therefore, the machines with the 1.0 power factors.tend to be more efficient at off-design-point speeds as well.

The seven pole pair machines synthesis results did not favor the 1.0 power factor machines nearly as much. For these designs, although the similar weight savings are obtained, the 1.0 power factor machines' eaf values are generally lower than the eaf values for the 0.8 power factor machines. Therefore, the motor speed near independence of the field current loss terms act to reduce the off-design-point performance of these motors. The values for off-design-point efficiency are generally bounded by the corresponding values for the 0.8 power factor machines with the 1.0 power factor efficiencies falling into the top end of the bounds.

Using the Speed Averaged Efficiency, the same inconsistency occurs. For the 3 pole pair motor case, the average is better in all cases. In fact, all of the 1.0 power factor motors were superior in averaged speed efficiency than the best speed efficient design of the 0.8 power factor designs (That design was not used in Chapter 4 due to its higher value of the Effective Weight objective function). This was not the case for the 7 pole pair machines. Here, the worst of the designs had a lower speed average than the 7 pole pair 0.8 power factor motor. Looking at all the 0.8 power factor motors, one of the highest Effective Weight designs had a speed averaged efficiency of 0.972 which was superior to all of the 7 pole pair designs regardless of power factor.

The results of this analysis are inconclusive. The "best" efficiency results for both the 1.0 and 0.8 power factor machines are within a few percent. Additionally, a review of the raw data with the speed averaged efficiency calculated showed that in many of the cases, designs that were removed from consideration due to high Effective Weight were superior to the "best" design (obviously, in those cases, the more efficient motors were significantly heavier than the "best" motors and that drove the Effective Weight).. The possible conclusions are that in some cases, heavier motors are more efficient or that the objective function may not be optimal.

Further investigation would be necessary to see if the technique could be used to further improve the off-design-point efficiency of the motors. The technique does, however, show the promise in reducing the weight of the machines by reducing the amount of conductor material due to reduced current carrying requirement. This reason alone makes further investigation in follow on studies advisable.

5.6 Objective Function Efficiency Enhancement

The preceding paragraphs discuss how the "as designed" motor performance could be enhanced for better off-design-point efficiency. An alternative method would be to design the motors for good performance by means of a different objective function.

In developing the motor designs, "Effective Weight" is used in the synthesis code as a "goodness parameter" or objective function in order to optimize the motor. This concept uses the full load efficiency of the motor to calculate the marginal impact of the efficiency on the weight of the propulsion plant. As stated in Chapter 1, this objective function takes the form of:

$$\text{Effective Weight} = \text{Motor Weight} + k_\eta(1 - \eta) + k_v v$$

where η and v are the overall efficiency and envelope volume of the motor design and k_η and k_v are the weighting factors for efficiency and volume. Therefore, when the program

executes, off-design-point performance is ignored and only the actual weight, full load efficiency and volume of the motor are dealt with.

If in fact, the designer must be concerned with how the motor operates at a variety of speeds, then such concerns are better dealt with at the outset when the objective function is initially developed. Noting that the volume impact of motor volume throughout this study was minimal, a more reasonable plan would be to start with a new objective function such as:

$$\text{Effective Weight} \quad = \quad \text{Motor Weight} \quad + \sum P(\nu_i) \bullet (1 - \eta(\nu_i)) \bullet M_i$$

where:

$P(\nu)$:	Speed probability density function for the ship's projected operations.
$\eta(\nu)$:	Motor efficiency as a function of the selected motor speeds.
M :	The efficiency - weight conversion and weighting factors as a function of motor speed.

Using this as the objective function, the minimization of the Effective Weight now reflects the "best" performance of the ship as it is expected to operate.

Implementation of this type of synthesis would involve marrying the current synthesis code with the synchronous motor efficiency program and resolving differences in variable and array usage and declaration. Such an effort is recommended as a follow on to this study.

A common practice in mathematical programming is to force an optimization to explore solutions with particularly desired characteristics (such as high efficiencies). The so-called "Big M" method [16] is one means by which this could be done. In the analysis done in this study, the efficiency marginal weight factor k_η reflects the actual impact of motor efficiency on the ship's Weight Group 2 weight. Since Effective Weight is only a measure of goodness for the motor, one can force very high efficiencies on the optimum design by forcing extremely

high penalties for efficiencies not approaching unity. By making the values of M as a function of speed very large (ie a "big" M) in the new objective function above, any value of the efficiency significantly different than unity will result in a very high Effective Weight and a design solution that will not likely be carried further. Such an effort is recommended as a follow on to this study.

Chapter Six: Conventionally Conducting D. C. Homopolar Motors

6.1 Drum Style Homopolar D.C. Machines General Discussion

In its simplest form, a homopolar motor consists of a rotor electrically connected in series to a fixed concentric stator. A radial magnetic flux field interacts with the current in the two conductors generating torque and rotor motion.

Electrically, homopolar motors are high current, low voltage machines. Currents on the order of one hundred kiloamperes are not unreasonable for homopolar motors. The high currents are part of the reason that practical homopolar motors are not common. The electrical connection between the fixed stator and the moving rotor must carry these very high currents without significant resistive losses. For example, a one hundred kiloampere current would generate 100 kilowatts of joule heating across a 10 micro-ohm connection or one megawatt across a tenth of a milliohm. Making very low resistance, high current density connections between fixed and rotating concentric cylinders was a problem in materials engineering that had to be solved for homopolar motors to be practical. The solution used by the designs considered in this study is liquid metal "brushes" or current collectors. Highly conducting liquid metals are injected into gaps machined into the stator where the transmission of electrical current is to occur The liquid "wets" the surfaces of the rotor and stator so that the current flow is uniform across the entire surface with no "hot spot" high resistance points occur.

The liquid metal used is a eutectic alloy of sodium and potassium (denoted by its chemical symbol: NaK). The NaK combines excellent fluid wetting characteristics with the necessary electrical conductivity to support the current densities required to make the motors feasible. It must be noted that this is not an optimum choice since these two metals react violently when exposed to water. In a marine application, extreme care must be taken to keep the liquid metal isolated from the water that the ship is moving in. This is not a problem in routine operation since the liquid metal must be isolated from air to prevent oxidation of the

NaK (and loss of conductivity) so the machine is air and water tight. Under abnormal or casualty conditions where it would be necessary to open the motor or to replenish the NaK charge, the possibility of water contact has to be accounted for by the motor designer.

The incompatibility of the NaK with water and the loss of conductivity that occurs when the NaK corrodes with contact with air has another significant effect. Water or air cooling of the motor to remove the waste heat caused by the ohmic losses is impractical. An oil based cooling system is used to remove the waste heat. The differences in fluid and thermodynamic characteristics of oil preclude current densities as high as those used in the synchronous motor applications discussed in earlier chapters. Maximum values for allowed current density in an oil cooled conductor are on the order of seven to eight megaAmperes per square meter.

Other, possibly more attractive options are being investigated, but to date, only NaK has carried sufficient currents for naval propulsion application.

6.2 Homopolar Motor Specific Design Discussion

The motors used here are based on the marine motor design developed at the David Taylor Research Center (DTRC) in Annapolis, Maryland. The motor is constructed of active and end modules. The end modules serve to seal the motor (airtightness requirement) and to close the magnetic flux current circuit for the extreme active modules. The end modules are basically the motor's "endcaps".

For the purposes of this study,active modules consist of a rotor-stator combination connected by two current collectors at the extreme ends of the module. In this design type, active modules come in pairs so the current collectors at the junction of the two modules is replaced by a single, double sized collector. This simplifies fabrication of the motor. The active modules are electrically connected in series.

The rotor encloses a large, iron core electromagnet that generates the required magnetic field. The field coils are in series with the armature and located on the steel electromagnet core near the current collectors. Two sets of field coils per module are installed at the extremities of the module. Current flow through the coils is such that their individual flux lines oppose each other along the axis of the motor. The magnetic flux is then "forced" to bend towards the rotor/stator, returning through the outer back iron on the stator and down the other side of each current collector. This opposing field flux paths do not utilze the center of the magnet core between the module field coils for the MMF circuit as the flux lines "bend away" from each other torward the stator. Significant weight savings result from the hollowing out of the unutized portion of each module's magnet core .

Dimensionally, the radius of the motor is principally driven by the radius of the electromagnet core and the balancing of the field required along the effective length of the rotor and the saturation of the iron core. Motors with relatively low numbers of modules require larger radii to achieve the needed air gap magnetic radial flux density given the saturation flux limits of the iron core.

Thus, one major tradeoff in both size and weight of the motor consists of varying the number of active modules. In simplest terms, to generate the required torque, for a given current and saturation magnetic flux, the surface area carrying the current and exposed to the flux is approximately fixed. By varying the number of active modules, the number of "hollow spots" in the bore of the electromagnetic iron core increase. The radius of the motor can be reduced as the total surface area for which a set of coils is generating flux is reduced so the area of the bore required to support the near saturation condition is reduced. These weight savings are balanced against the accompanying increase in current collectors, field coils and so on, associated with additional modules. The effective area increases further in order to offset the additional electrical losses these components accrue.

6.3 Loss Terms

Losses in the homopolar motor are generally the same as for most motors. Ohmic losses in the copper current paths, principally the rotor, stator and field coils comprise the bulk of the energy lost to the output of the machine. The calculation of these loss terms are consistent with the techniques used for the synchronous machines.

Unique to the D.C. machine, however are loss terms associated with the brushes. The losses can be attributed to electrical losses, again a straight forward ohmic loss term, and mechanical losses associated with the brushes imparting drag resistance on the moving rotor. The ohmic losses are dealt with geometrically, calculating the resistance of the cylindrical shell of the brush. The drag force is calculated using empirical relations provided by the David Taylor Research Center relating the speed of the rotor to frictional drag (power lost proportional to speed squared) and to fluid viscous drag (power lost proportional to speed cubed).

6.4 Machine Design Description

Motors with rated power speeds of 120 and 720 rpm were modeled using ten to thirty active modules (20 to 60 current collectors). Below ten collectors, the motors would not meet the requirement to fit in the submarine as envelope diameter increased rapidly. Since this design program is deterministic in nature, only one run per collector number was performed. Effective Weight was then calculated in order to compare the results among the like design candidate motors.

6.4.1 120 RPM Direct Drive Analysis

Efficiency

As the number of modules increase, the number of field coils and brushes increase. Therefore, losses resulting from these components increase as well. In addition, since these

losses must be overcome, the electromagnetic length of the motor increases so the resistive losses on the rotor and stator also increase. This results in the full load efficiency of the motors being a decreasing function of the number of modules and the number of current collectors. Efficiency varies from approximately 94 to 98 percent for the motors considered as compared to 92 to 98 percent for the comparable A.C. synchronous machines.

Weight and Volume

Weight and volume are strong functions of the number of current collectors, decreasing strongly until reaching minimums at 48 and 56 collectors, respectively. Weights varied from a minimum of just over 102 metric tons to a maximum of 154 metric tons. Volume varied from a minimum of just over 22 cubic meters to 45 cubic meters. This compares to 61 to 100 metric tons and 10 to 33 cubic meters for comparable A.C. synchronous machines. Tables 6.1 and 6.2 and Figures 6.1 through 6.3 apply.

6.4.2 720 RPM Gear Reduced Drive Analysis

Efficiency

The variation of efficiency versus the number of current collectors was much the same for the gear reduced machines as for the direct drive motors. The efficiency of the 720 rpm designs were not significantly better than the direct drive machines. This is primarily due to the speed dependency of the brush drag losses. These losses are 15 to 40 times greater for the 720 rpm machines than for the comparable direct drive motors. Efficiencies of 95 to 98 percent were obtained as compared to 96 to 98.5 percent for the comparably rated A. C. synchronous motor designs. If the efficiency of the single stage gearing system is included using the 1% per reduction stage rule of thumb used by [1], then the net efficiency of the motor unit is 94 to 97 percent .

Weight and Volume

Motor weight varies from a minimum of 24 metric tons to a maximum of 35 metric tons. Volume varied from a minimum of 6.5 cubic meters to a maximum of 8 cubic meters. This compares to 15 to 25 metric tons and 2.7 to 10 cubic meters for comparable A.C. synchronous machines. Including the reduction gear required for these motors (40.7 metric tons and 9.5 cubic meters), the gear reduced designs are still significantly better volume and weight bargains than the direct drive machines. The gross dimensions of the propulsion unit of the motor and the reduction gear (for the 720 rpm motors) are roughly the same when the 3 to 4 meter diameter of the reduction gear and the 1 to 1.5 meter increase in total length are taken into account. Tables 6.3 and 6.4 and Figures 6.4 through 6.6 apply.

Table 6.1 120 RPM Homopolar Motor Data

25,000 HP

Current Collectors	20	24	28	32	36
Dimensions					
Envelope Diameter (m)	2.99	2.77	2.61	2.49	2.39
Envelope Length (m)	6.41	6.18	6.07	6.02	6.03
Armature Inner Radius (m)	1.01	0.93	0.87	0.82	0.78
Armature Outer Radius (m)	1.16	1.090	1.03	0.99	0.96
Bore Radius (m)	0.94	0.87	0.81	0.76	0.72
Electromagnetic Length (m)	3.45	3.39	3.36	3.38	3.42
Field Coil Length (m)	0.19	0.23	0.27	0.30	0.34
Total Volume (m^3)	45.0	37.4	32.6	29.3	27.1
Total Weight (kg)	154,830	134,560	121,990	113,850	108,560
Electrical Parameters					
Rated Input Voltage (V)	193.0	193.5	194.1	194.6	195.2
Rated Armature Density (MA/m^2)	7.80	7.80	7.80	7.80	7.80
Rated Armature Current (kA)	98.2	98.2	98.2	98.2	98.2
Rated Field Density (MA/m^2)	7.75	7.75	7.75	7.75	7.75
Loss Terms					
Field Current (KW)	138.5	145.3	153.2	160.8	168.4
Armature Current (KW)	285.0	327.3	373.3	421.8	473.6
Other	22.1	26.5	31.2	37.8	45.5
Efficiency					
120 RPM	0.977	0.974	0.971	0.968	0.965

Table 6.2 120 RPM Homopolar Motor Data

25,000 HP

Current Collectors	40	44	48	52	56
Dimensions					
Envelope Diameter (m)	2.31	2.25	2.20	2.15	2.12
Envelope Length (m)	6.06	6.12	6.20	6.30	6.41
Armature Inner Radius (m)	0.74	0.71	0.69	0.67	0.65
Armature Outer Radius (m)	0.93	0.91	0.90	0.89	0.88
Bore Radius (m)	0.69	0.66	0.63	0.61	0.60
Electromagnetic Length (m)	3.48	3.55	3.64	3.74	3.84
Field Coil Length (m)	0.38	0.42	0.46	0.50	0.54
Total Volume (m^3)	25.5	24.3	23.5	22.9	22.6
Total Weight (kg)	105,240	103,270	102,290	102,050	102,570
Electrical Parameters					
Rated Input Voltage (V)	195.9	196.6	197.3	198.1	198.9
Rated Armature Density (MA/m^2)	7.80	7.81	7.81	7.81	7.82
Rated Armature Current (A)	98.2	98.2	98.2	98.2	98.2
Rated Field Density (MA/m^2)	7.75	7.75	7.75	7.75	7.75
Loss Terms					
Field Current (KW)	175.8	182.6	188.6	193.8	199.3
Armature Current (KW)	529.1	588.1	650.9	717.1	788.3
Other	53.0	61.9	72.8	86.8	93.8
Efficiency					
120 RPM	0.961	0.957	0.953	0.949	0.945

Figure 6.1: 120 RPM HOMOPOLAR MOTOR EFFICIENCY
25,000 HP

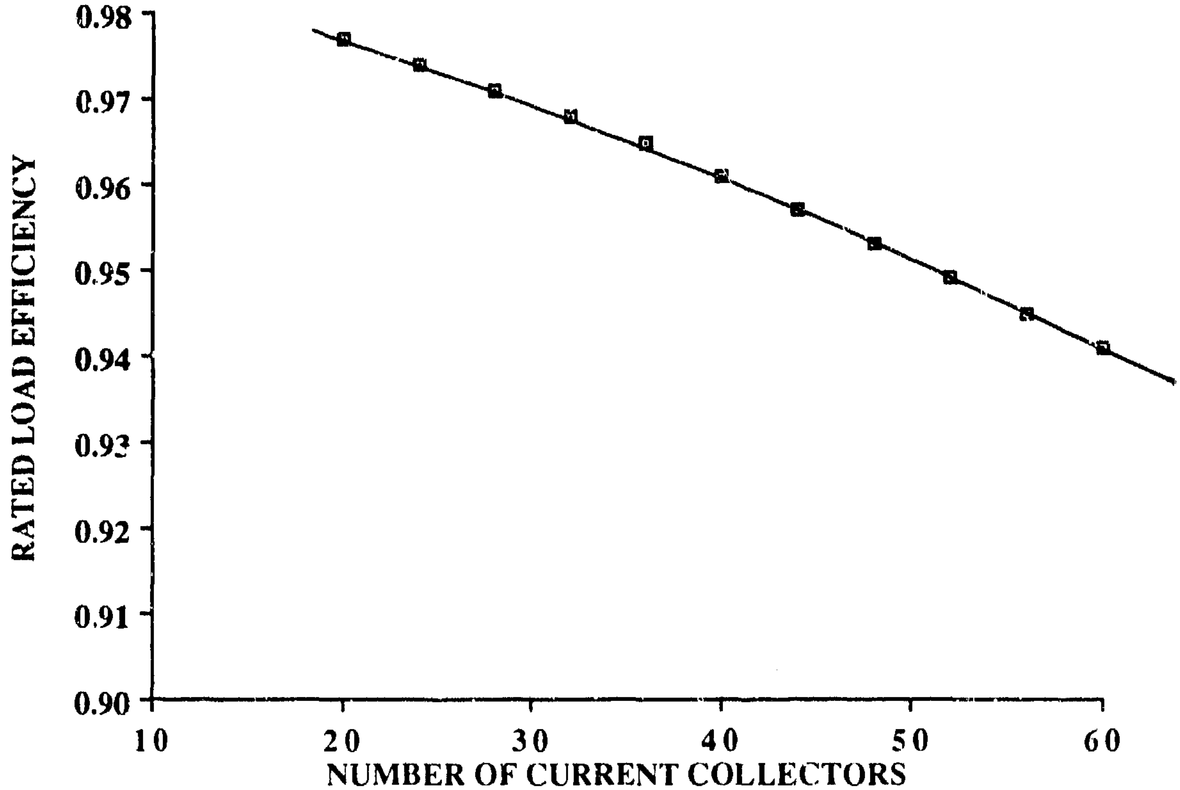


Figure 6.2: 120 RPM HOMOPOLAR MOTOR WEIGHT
(Kilograms)

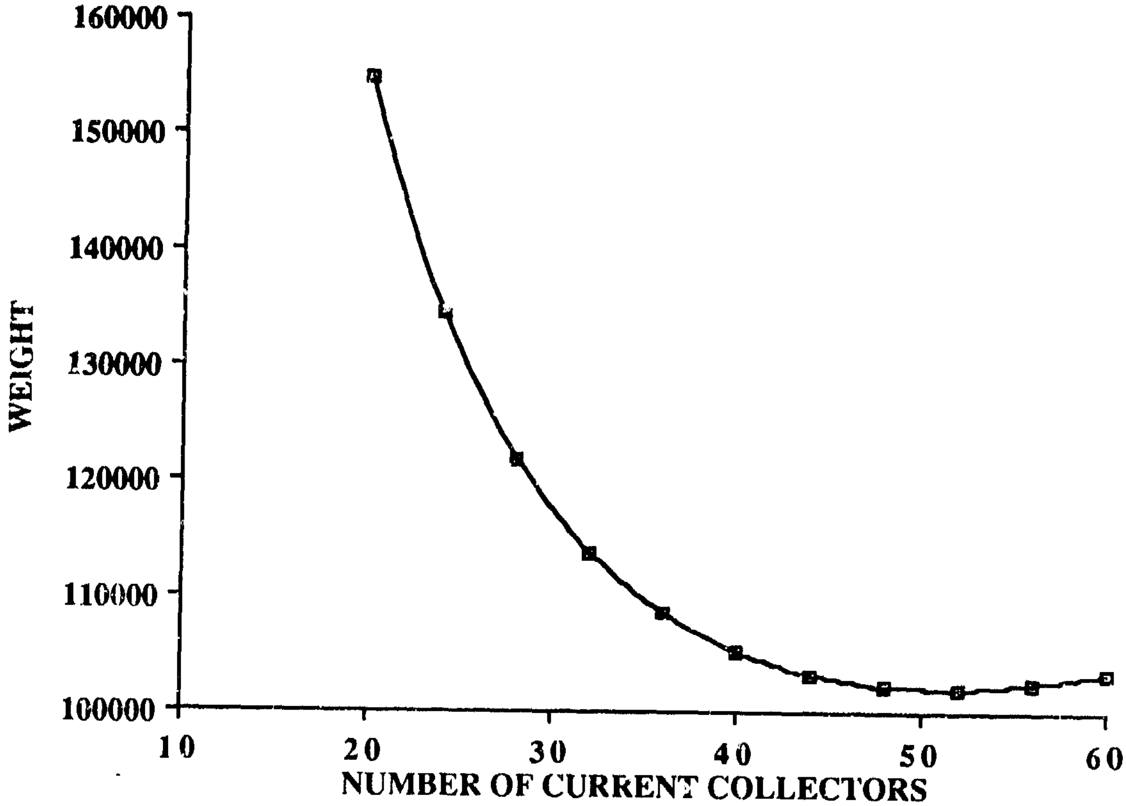


Figure 6.3: 120 RPM HOMOPOLAR MOTOR VOLUME

(Cubic Meters)

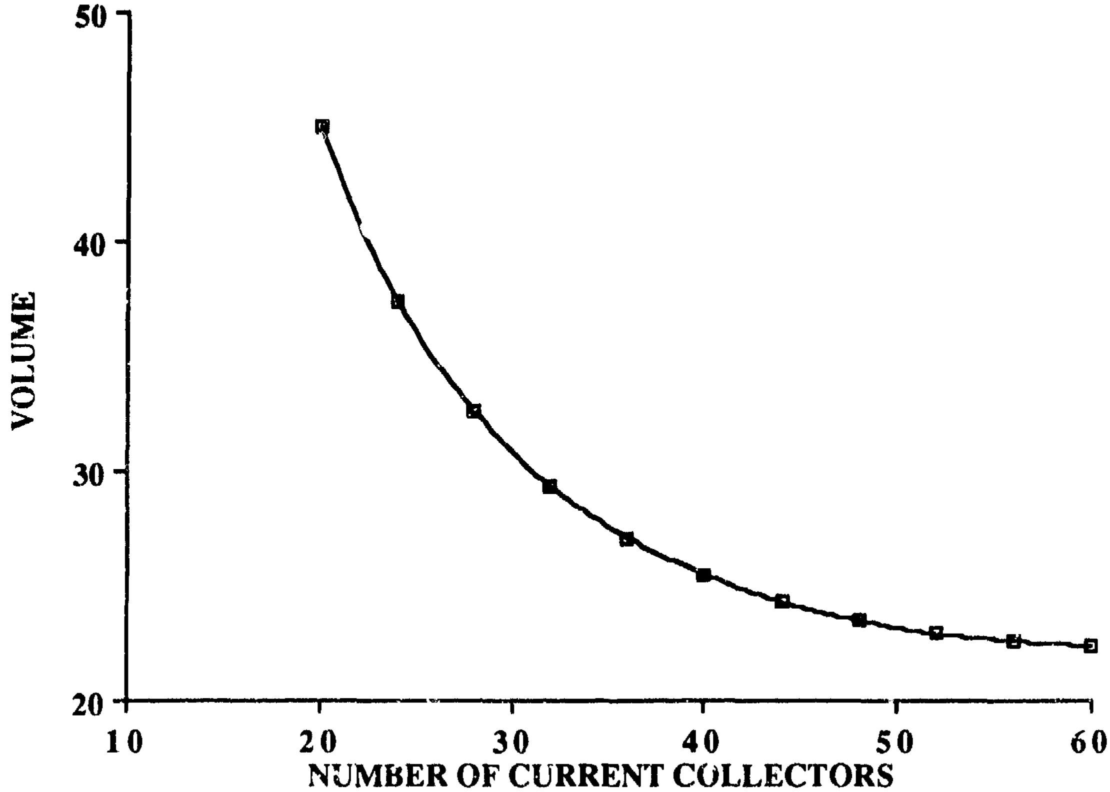


Table 6.3 720 RPM Homopolar Motor Data

25,000 HP

Current Collectors	20	24	28	32	36
Dimensions					
Envelope Diameter (m)	1.52	1.45	1.41	1.38	1.36
Envelope Length (m)	4.03	4.11	4.22	4.35	4.50
Armature Inner Radius (m)	0.48	0.45	0.42	0.40	0.39
Armature Outer Radius (m)	0.65	0.62	0.61	0.60	0.60
Bore Radius (m)	0.40	0.37	0.35	0.34	0.33
Electromagnetic Length (m)	1.86	1.95	2.06	2.18	2.31
Field Coil Length (m)	0.20	0.24	0.28	0.32	0.036
Total Volume (m^3)	7.32	6.79	6.56	6.49	6.54
Total Weight (kg)	24,630	23,990	24,190	24,890	25,940
Electrical Parameters					
Rated Input Voltage (V)	191.7	192.1	192.6	193.1	193.7
Rated Armature Density (MA/m^2)	7.83	7.83	7.84	7.84	7.84
Rated Armature Current (A)	98.8	98.8	98.8	98.9	98.9
Rated Field Density (MA/m^2)	7.75	7.75	7.75	7.75	7.75
Loss Terms					
Field Current (KW)	79.8	84.2	87.8	90.1	91.3
Armature Current (KW)	144.2	176.8	214.0	255.9	302.3
Other	155.6	161.8	172.4	187.1	205.4
Efficiency					
720 RPM	0.980	0.978	0.975	0.972	0.967

Table 6.4 720 RPM Homopolar Motor Data

25,000 HP

Current Collectors	40	44	48	52	56
Dimensions					
Envelope Diameter (m)	1.35	1.35	1.35	1.36	1.37
Envelope Length (m)	4.65	4.82	4.99	5.17	5.35
Armature Inner Radius (m)	0.37	0.36	0.35	0.34	0.34
Armature Outer Radius (m)	0.60	0.60	0.61	0.61	0.62
Bore Radius (m)	0.32	0.31	0.30	0.30	0.30
Electromagnetic Length (m)	2.45	2.60	2.75	2.90	3.06
Field Coil Length (m)	0.32	0.44	0.48	0.52	0.56
Total Volume (m^3)	6.66	6.89	7.18	7.52	7.92
Total Weight (kg)	27,270	28,940	30,830	32,940	35,250
Electrical Parameters					
Rated Input Voltage (V)	194.4	195.1	195.8	196.5	197.3
Rated Armature Density (MA/m^2)	7.84	7.85	7.86	7.87	7.88
Rated Armature Current (A)	98.9	99.0	99.1	99.2	99.3
Rated Field Density (MA/m^2)	7.75	7.75	7.75	7.75	7.75
Loss Terms					
Field Current (KW)	91.6	91.6	91.04	90.1	88.8
Armature Current (KW)	353.1	409.7	471.3	538.1	610.1
Other	231.4	252.4	275.8	301.6	329.9
Efficiency					
720 RPM	0.965	0.961	0.957	0.953	0.948

Figure 6.4: 720 RPM HOMOPOLAR MOTOR EFFICIENCY
25,000 HP

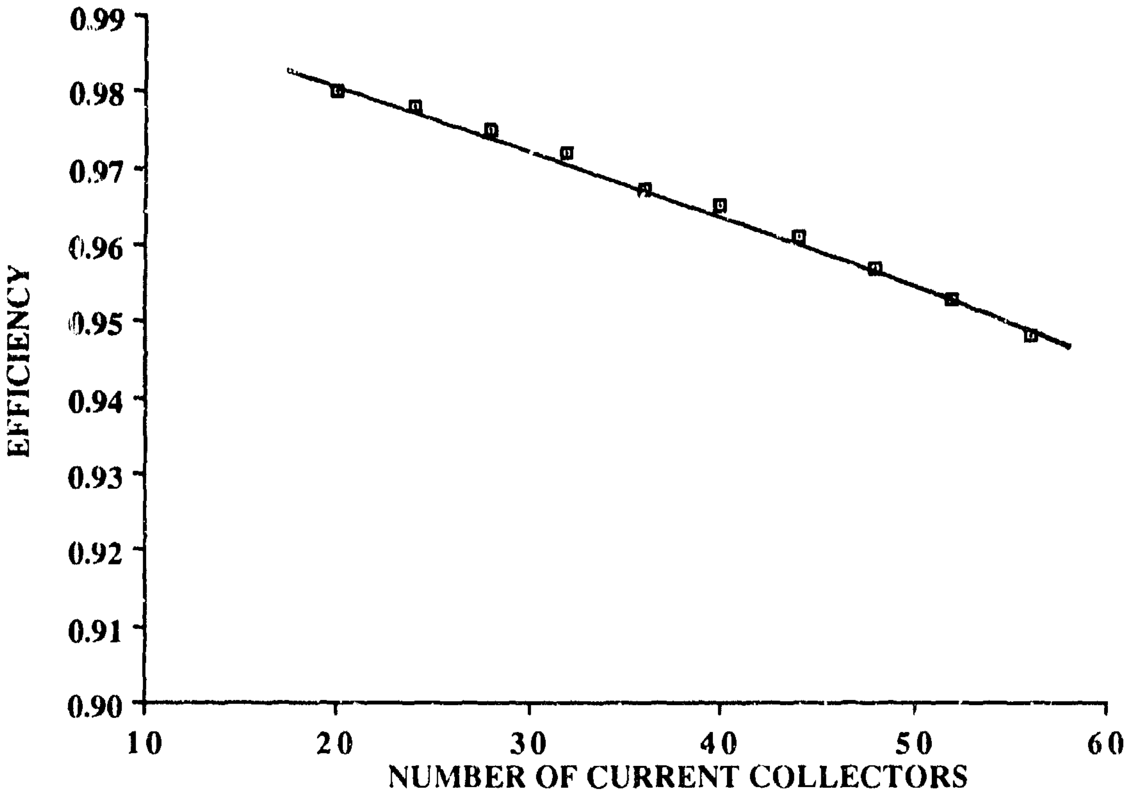


Figure 6.5: 720 RPM HOMOPOLAR MOTOR WEIGHT

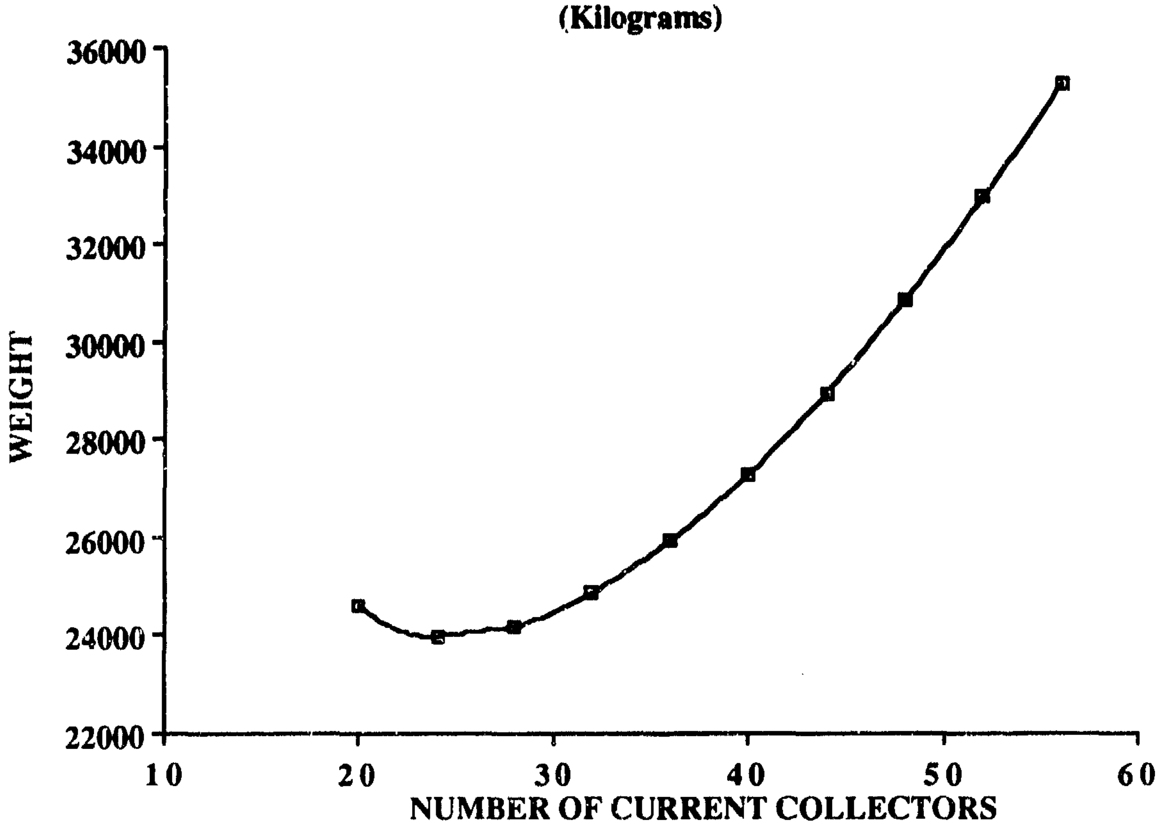
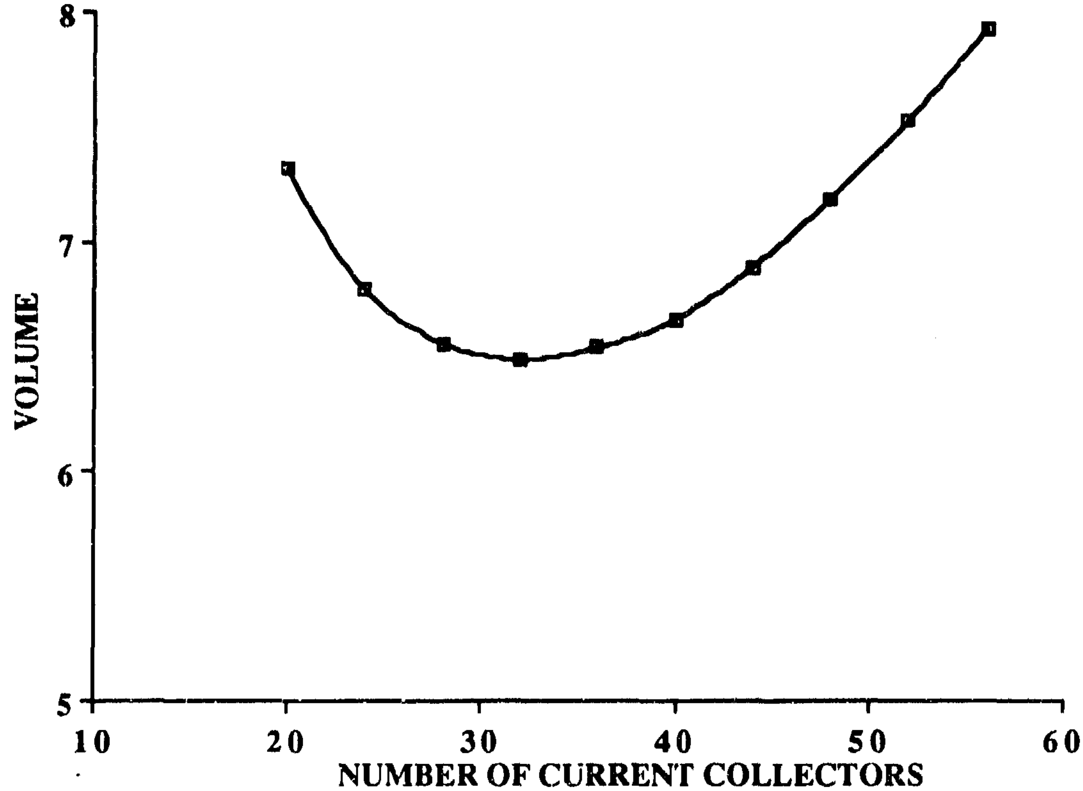


Figure 6.6: 720 RPM HOMOPOLAR MOTOR VOLUME
(Cubic Meters)



Calculating the Effective Weight parameter manually, the motor designs with the best value of Effective Weight are the 52 current collector (26 active modules) motor for the direct drive motors and the 24 current collector (12 active modules) motor for the direct drive case. The "best" direct drive motor weighs 102.0 metric tons, requires 22.9 cubic meters of volume and is 95 percent efficient. This compares to 61.4 metric tons, 11.4 cubic meters and 94 percent for the direct drive synchronous motor of choice. The "best" gear reduced drive motor weighs 24 metric tons, requires 6.8 cubic meters of volume and is 98 percent efficient compared to 15.9 metric tons, 3 cubic meters and 98 percent.

6.5 Off-Design-Point Efficiency

For D.C. motors, efficiency is driven by the type of excitation that is used in the design of the motor. Separately excited field windings are the design of choice for a superconducting motor design. The superconducting motor uses zero resistance, superconducting coils to generate the required magnetic fields. The field losses are essentially zero since only the minimal losses associated with connecting the current source to the field coils need to be reckoned with.

This is not the case for the conventional, normally conducting field coil machine considered here. For example, consider a 25,000 horsepower (18.65 Mwatt), separately excited motor with field current copper losses of 140 kilowatts. Assuming mechanical power is proportional to the cube of the motor's rotational speed (Ω_{mech}^3), then the mechanical output power at twenty percent of rated motor speed is approximately 150 kilowatts. Therefore, the best that the efficiency could be is 150/(140+150) (ignoring other loss terms) for a value of 52 percent. A different field scheme is obviously required.

6.5.1 Homopolar Motor Equations

The torque (T) generated by the drum conductor current (I_a) in the presence of a magnetic field (B) is given by

$$T = B\,I_a\,r\,l$$

where r and l are the radius and effective length of the conductor respectively. The mechanical output power is the product of the torque and the rotational speed speed of the motor. Since the magnetic field is proportional to the field current generating the field, then for a series excited motor ($I_a = I_{field}$), the output power is proportional to $I_a^2\,\Omega_{mech}$. Using the pump law approximation again, the off-design-point power of the motor is a function of cube of the motor speed (Ω_{mech}) or

$$P_{out} = P_{rated} \cdot \left[\frac{\Omega_{mech}}{\Omega_{rated}} \right]^3$$

Combining the two expressions, we obtain a relation:

$$\Omega_{mech} = K\, I_a$$

where K is a constant based on the geometric dimensions of the motor. Thus, output mechanical power and armature current can be calculated as functions of the motor speed and the rated operation performance. From the above, and including the other loss terms of the motor, the input power of the motor can be calculated as:

$$P_{in} = P_{out} + I_a^2\,(R_{arm} + R_{field}) + \text{brush losses}$$

and then the off-design-point efficiency of the motor can be calculated as a function of speed by the standard form:

$$\eta = \frac{P_{out}}{P_{in}}$$

Speed is controlled by the varying of the voltage applied to the input terminals of the motor. In the example considered for the seperately excited motor, then all of the loss terms are proportional to motor speed raised to the second (or higher) power. If the motor was 95% efficient at rated power, then the total losses at 20 % rated speed would be approximately 37 kilowatts and motor efficiency would be approximately 0.80.

Finally, voltage as a function of speed is given by:

$$V_{applied} = \frac{P_{in}}{I_a}$$

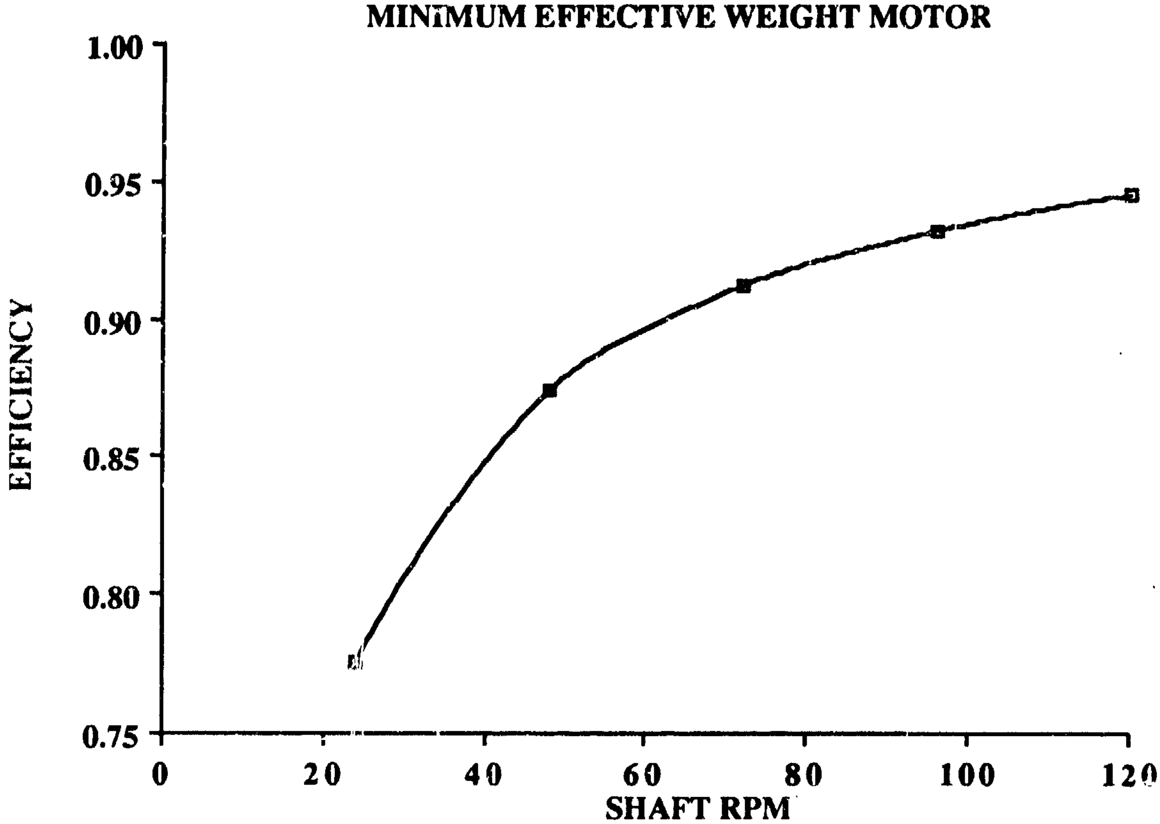
where P_{in} and I_a are the values calculated above for the speed of interest.

6.5.2 Off-Design-Point Direct Drive Efficiency

The off-design-point efficiency of the minimum effective weight direct drive homopolar motor design was determined and is presented in Figure 6.7. The speed averaged efficiency (using the speed profile probability density function posed in Chapter Five) is 0.898. This compares to values of 0.87 to 0.88 for the various techniques used in Chapter Five for the minimum effective weight synchronous direct drive motor.

Figure 6.7: 120 RPM HOMOPOLAR MOTOR EFFICIENCY

MINIMUM EFFECTIVE WEIGHT MOTOR

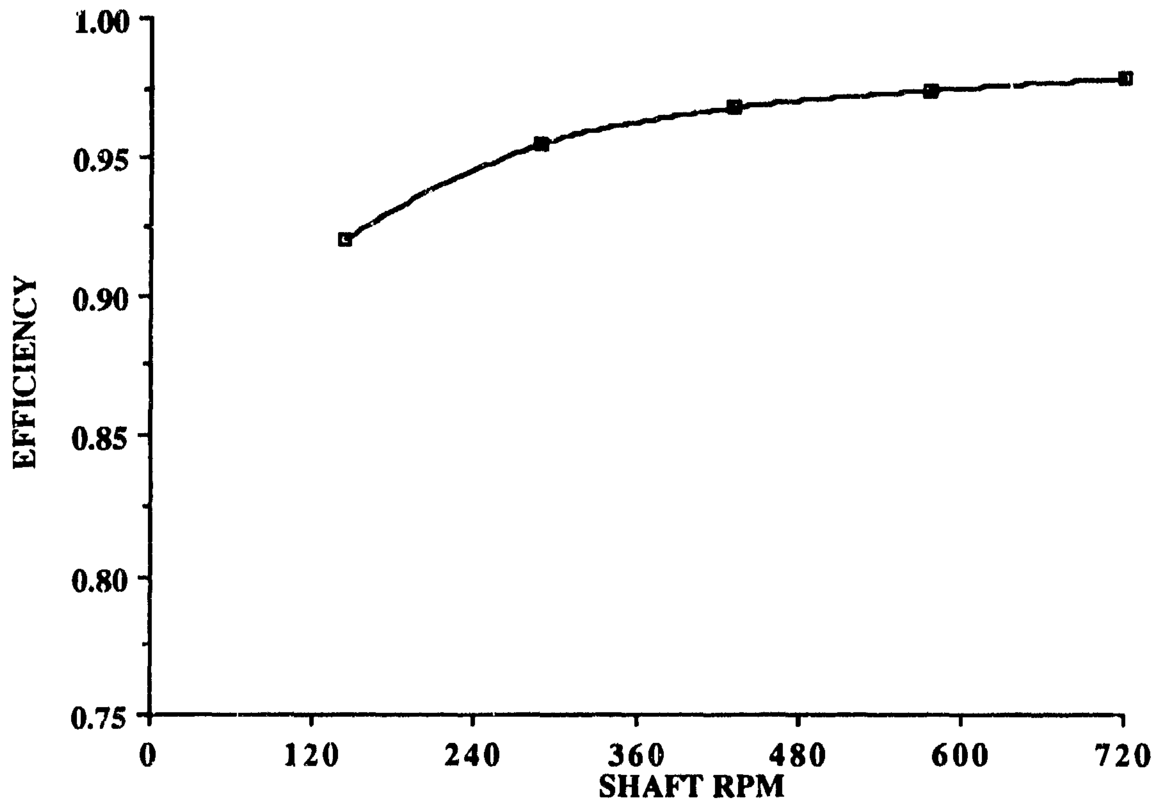


6.5.3 Off-Design-Point Gear Reduced Drive Efficiency

The off-design-point efficiency of the minimum effective weight gear reduced drive homopolar motor design was determined and is presented in Figure 6.8. The speed averaged

efficiency for this motor is 0.963. Although speed averaged efficiency was not presented for this motor in Chapter Four, this compares to a value of 0.976 for the minimum effective weight synchronous gear reduced drive motor.

Figure 6.8: 720 RPM HOMOPOLAR MOTOR EFFICIENCY
MINIMUM EFFECTIVE WEIGHT MOTOR



Chapter Seven: Electric Drive Submarine Naval Architecture

This chapter is the point of the study. It is where the answers to the key question "What does electric drive do to a submarine?" are explored. For continuity and utility, this chapter parallels the comparable chapter of [1]. There are, however, two significant differences. First, without a tool such as the ASSET program used by Davis, the ship designs considered are what Davis called "backfits". In other words, this study only examines the impacts of electric drive on the control baseline ship designed in Chapter Three. The nonavailability of a computer aided synthesis tool precludes development of a useful, electric drive design from first principles.

Secondly, the basic design of the rest of the ship will not be changed unless required to make a candidate design feasible. No provision will be made for additional or less fuel loading and no significant rearrangement (where not directly a result of the electric drive installation) will be considered. Submarines, by the enclosed nature of the working and living space, do not have the three dimensional freedom of arrangement employed by Davis in the designs he presented. The new equipment must be installed in approximately the same location as the components that are removed from the baseline.

Five variants will be considered. The mechanical baseline ship (MECH), direct drive D.C and A.C. (DCDD and ACDD) driven ships and gear reduced D.C and A.C. (DCGD and ACGD) driven ships.

7.1 Direct Effects

Direct effects are those changes in weight and volume associated with the removal of mechanical drive components and the installation of the electrical components.

Specific weights and volumes were obtained from a variety of sources. Detailed weight and volume data is not generally available for actual submarine components. ASSET based

algorithms [15] used by Davis [1] were used to estimate component weight and volume for items such as power transmission lines, switchgear, reduction gears and power converters. Propulsion generator weights were estimated using the synthesis programs for a 3600 rpm prime mover which is a reasonable speed for a marine steam turbine. The generators and power converters were intentionally overrated to 15,000 horsepower to provide single generator operation at 60% rated plant power. D.C. propulsion rectifier weights and volumes were provided by DTRC. The DTRC homopolar motor design code includes auxiliary control component impacts in the motor weight and volume output. The propulsion generator drive turbines and the associated control systems.were assumed to be comparable in volume and weight to the mechanical drive turbines and mechanical control systems already in place. Where other sources of information such as [9,14] were available, these estimates were checked for consistency. Positive deltas indicate that the variant value is larger than the mechanical baseline. A more detailed break out is presented in Tables 7.1 and 7.2.

Table 7.1 Direct Weight Effects (Weights in Long Tons)

Component	MECH	DCDD	DCGD	ACDD	ACGD
Main Motor	-0-	100.8	23.6	60.2	15.6
Generators	-0-	-0-	-0-	10.2	10.2
Generator/Rectifiers	-0-	12.0	12.0	-0-	-0-
Transmission Lines	-0-	0.1	0.1	0.1	0.1
Switchgear	-0-	1.0	1.0	1.0	1.0
Power Converters	-0-	-0-	-0-	14.1	14.1
Braking Resistance	-0-	-0-	-0-	4.9	4.9
Reduction Gears	72.2	-0-	40.7	-0-	40.7
Totals	72.2	113.9	77.4	89.5	86.6
Deltas to the Baseline	-0-	+41.7	+5.2	+17.3	+14.1

All electric drive variants are heavier than the mechanical baseline. Therefore, in order to maintain the neutral buoyancy, lead ballast will have to be removed from the ship. Adjustment of the trim condition and determination of the final lead solutions will be calculated later in the chapter.

Table 7.2 Direct Volume Effects (Volumes in Cubic Feet)

Component	MECH	DCDD	DCGD	ACDD	ACGD
Main Motor	-0-	796.2	239.3	401.6	96.5
Generators	-0-	-0-	-0-	61.5	61.5
Generator/Rectifiers	-0-	200.0	200.0	-0-	-0-
Transmission Lines	-0-	2.4	2.4	2.4	2.4
Switchgear	-0-	46.8	46.8	46.8	46.8
Power Converters	-0-	-0-	-0-	634.2	634.2
Braking Resistance	-0-	-0-	-0-	690.1	690.1
Reduction Gears	2947.4	-0-	317.1	-0-	317.1
Totals	2947.4	1045.4	805.5	1836.6	1848.6
Deltas to the Baseline	-0-	-2142.2	-1902.0	-1110.8	-1098.8

In all cases the electric variants are less volume intensive than the mechanical baseline. None of the hulls can be reduced in size, however, because there is no accompanying reduction in the W2 weights. The existing hull volume is still required to provide the buoyancy that balances the submarines weight.

7.2 Indirect Effects

There are no indirect effects on the design of ship resulting from the installation of electric drive. The fuel load is fixed and the same propeller is used in all five design variants.

7.3 Design Analysis

For each variant, the new transmission components were arranged in the envelope of the mechanical baseline hullform. Weight Group 2 weights, longitudinal and vertical centers of gravity were recalculated for each design. Leaving the other weight groups fixed, Condition A-1 was determined for each design and the overall lead required to close the designs to the same Condition A as the mechanical baseline. Closure to the same Condition A forces consistency with the rest of the mechanical baseline's design characteristics including Normal Surfaced Condition, Main Ballast Tank weight and Submerged Displacement. Therefore, the five designs behave identically hydrodynamically and hydrostatically in both the surfaced and the submerged conditions. All five design variants meet the same stability requirements as the mechanical variant without having to recalculate the stability parameters. An infeasible lead solution (ie lead can not be reasonably positioned in the ship and balance the trim), indicates that significant rearrangement or hull design modification is necessary for that design to be feasible. Table 7.3 summarizes the W2, Condition A-1 and the Lead Solution for the five variants.

Table 7.3 Propulsion System Weight and Moment Summary

	WEIGHT (LTONS)	LCG (FEET)	VCG (FEET)
Mechanical Baseline:			
Weight Group 2	1158.8	165.1	14.1
Condition A-1	4138.6	144.1	15.2
Total Lead	413.9	142.5	13.7
Stability Lead	68.0	141.0	2.0
Margin Lead	345.9	142.8	16.0
DC Direct Drive:			
Weight Group 2	1199.5	167.4	14.1
Condition A-1	4179.8	145.0	15.2
Total Lead	372.7	132.7	13.3
Stability Lead	71.0	89.5	2.0
Margin Lead	301.8	142.8	16.0
DC Gear Drive:			
Weight Group 2	1163.0	165.4	14.1
Condition A-1	4143.26	144.2	15.2
Total Lead	409.2	141.4	13.7
Stability Lead	67.4	134.4	2.0
Margin Lead	341.9	142.8	16.0
AC Direct Drive:			
Weight Group 2	1176.1	166.0	14.2
Condition A-1	4156.4	144.4	15.3
Total Lead	396.14	138.9	13.4
Stability Lead	74.0	121.6	2.0
Margin Lead	322.2	142.8	2.0
AC Gear Drive:			
Weight Group 2	1172.2	165.9	14.2
Condition A-1	4152.5	144.4	15.3
Total Lead	400.0	139.4	13.4
Stability Lead	74.5	124.6	2.0
Margin Lead	325.6	142.8	16.0

All lead solutions are feasible. The location of the stability lead for the DCDD variant is quite far forward and positioning the lead ingots into suitable free flood spaces or voids may be difficult in actual practice. However, from a naval architectural point of view, all of the variant designs are feasible. It is clear that only the stability lead position is sensitive to the variant studied and that margin lead absorbs the bulk of the W2 variation. In a well designed submarine, this is as it should be and it indicates that the baseline ship was a good control design for the study.

The key conclusion that must be drawn from this analysis is that the ship designer can, if required, absorb electric propulsion into even a fairly mature mechanical drive submarine design without necessarily having to start from scratch or modify the hull. Future growth margin (in the form of margin lead) and future stability margin (in the form of stability lead locational flexibility) are sacrificed to install the equipment,. Additional arrangable volume is derived for all the electric variants compared to baseline, but the use of that volume for other new equipment

7.4 Propulsive Efficiency Impacts

The total efficiency for the propulsion plant is the product of the efficiencies of the various components involved in the generation of thermal energy and its ultimate conversion to kinetic energy of the ship.

Symbolically, this can be expressed as:

$$\eta_{total} = \eta_{thermal} \eta_{prop} \eta_{trans} \eta_{misc}$$

where:	$\eta_{thermal}$:	The thermal efficiency of the heat/steam generation cycle.
	η_{prop} :	The efficiency of the shaft and propeller.
	η_{trans} :	The efficiency of the transmission of power to the shaft.
	η_{misc} :	This term accounts for the various mechanical efficiency losses throughout the plant (for example, pump losses etc.).

In the five variants considered, the thermal and propeller efficiencies are identical since those components are unchanged from the baseline design. The miscellaneous efficiencies will be nearly equal since auxiliary components were not changed. Slight variation due to turbine efficiency differences between the generator and the mechanical drive turbines will be ignored. The transmission efficiency is the efficiency of the reduction gears for the mechanical baseline and the product of the efficiencies of the components from the output of the turbine driving the propulsion generator to the main shaft coupling.

Locked-train reduction gear efficiency is approximately

$$\eta_{rg} = (1 - \text{the number of reduction stages})$$

Generator efficiency is estimated as 0.992 by the synthesis program. Power converter efficiency was estimated to 0.97 by [1] and slightly higher by DTRC. The lower estimate is used for conservatism. D.C. generator/rectifier efficiency is estimated to be 0.98 by DTRC. The speed averaged efficiency (per Chapter Five) is used for the motor efficiency term. The net transmission efficiency for each of the variant designs is summarized in Table 7.4.

Table 7.4 Transmission System Efficiency Summary

Design Option	Transmission Efficiency
Mechanical Baseline	0.980
D.C. Direct Drive	0.880
D.C. Gear Reduced Drive	0.934
A.C Direct Drive	0.856
A.C. Gear Reduced Drive	0.930

In all cases, the additional energy conversion cycles from mechanical to electric to mechanical (generator to motor to motor output) degrade the transmission efficiency of the electric drive systems compared to the mechanical baseline systems. The fact that overall efficiency depends on these terms as a direct multiplier means that a 10 percent greater inefficiency on the part of the DCDD motor compared to the baseline causes the total propulsion plant to be 10 percent less efficient. There is a direct correlation to the amount of fuel provided and the operational schedule of the ship.

For example, assuming the same speed probability density function and the same operational schedule, the most efficient electric system would operate without refueling 95.6% as long as the mechanical baseline ship. The least efficient system would operate only 87.3% as long. Alternatively, over the typical thirty year life of the ship, the electric submarine would require five to twelve percent more fuel than the mechanical baseline. The fact that the propulsion plant weight is not driven by indirect factors, that is that the weight of the propulsion plant does not change significantly by use of electric drive, does not allow the designer to "shrink" the ship. Therefore, the reduced efficiency of the plant increases the lifetime operational cost to operate the ship.

7.5 The "Best" Design

The best choice of the electric drive plants from the parameters considered here is the D.C. Gear Reduced Drive plant. The design has the minimum impact on the ship, naval

architecturally, with only a minimal increase in weight (and decrease in margin) compared to the baseline and the minimum volume requirement o any of the five designs considered. Electrically, the higher speed designs are more efficient, only 5% more inefficient than the baseline which minimizes the operational and cost impacts of the system. The disadvantage of this system is the reliance on a mechanical reduction gear to drive the shaft at its most optimum speed range. Part of the reasoning involved in considering the electric drive systems was to eliminate mechanical linkages and metal on metal contact. There does not appear to be very much advantage in replacement of one geared system with another, less efficient, albeit smaller geared system.

The D.C. Direct Drive plant is the best option of the "no reduction gear" solutions. Although the heaviest of the five variants examined, it required less volume and was 3% more efficient than the A.C. Direct Drive design. The direct drive nature of the synchronous motor precludes any degree of commonality with surface ship designs that will in all likelihood use a large double reduction gear based system [1]. A key reason for examining the A.C. option was that commonality between surface ships and submarines could help defray the system procurement and life support costs. Without this advantage, the A.C. system has no significant advantages to recommend its use in lieu of the D.C option.

7.6 An Alternative Arrangement Design Concept.

The use of electric drive does provide some additional flexibility to the ship designer. To understand how this flexibility might be used, some background on the operation of marine steam plants is useful. After going through the turbines, the exhaust steam must be cooled and condensed back into liquid water so that the water can be pumped back into the boilers and close the steam cycle loop. The energy removed from the steam is the latent heat of vaporization. Large amounts of seawater is pumped through huge shell and tube heat exchangers (condensers) to remove this waste heat.

The condensers are located directly beneath the turbines. In a mechanical drive system, the turbines must as far aft as possible to minimize "wasted" space dedicated to extra lengths of shafting. A failure of the condenser's seawater system is a flooding casualty of major and potentially catastrophic proportions as the ship rapidly gains weight. Compounding the problem is the fact that the weight is (a) is as far aft in the ship as it could be and (b) comprised of water. The weight being brought in aft means that the weight generates a large unbalanced moment that imparts a large angle on the ship that impedes casualty control efforts and further degrades the stability of the ship. The fact that the weight is water permits what is called "the free surface effect". As the ship angle increases due to the added weight, the water seeks the lowest point which is now the aftmost portion of the ship, increasing the effective moment arm of the added weight, further increasing the angle.

The problem with large angles beyond the problems with moving about the ship, is twofold. First, the dynamic force of the ship's body shape decreases as the angle increases. This limits the ability of the ship to "drive" to the surface. Secondly, the ship's ability to rapidly increase its buoyancy is based on the ability to blow compressed air into its main ballast tanks. A large angle can cause the main ballast tanks to vent through the flood ports on the bottom of the ship, minimizing the utility of the main ballast tank blow. The larger the angle becomes, the sooner the flood ports will "uncover" during the blow, and the less the amount of buoyancy the ship gains. If the ship reaches the surface, a large angle is also a problem. The larger the angle on the ship, the smaller the cross sectional area that the hull "cuts" on the surface of the water. This cross sectional or "waterplane" area is a key parameter is determining damaged stability on the surface. It is not coincidental that many ship sinkings occur either bow or stern first. The ship angle increase reduces the area of the waterplane. The waterplane area can be thought of as the constant of proportionality between surfaced buoyant force and the amount of the ship that is below the surface of the water. As the waterplane area

decreases, more ship must "submerge" to balance ship weight with bouyancy. When coupled with rapid increase in weight from flooding, the ship sinks.

Electric drive permits the movement of the turbines and the condensers forward in the ship next to the reactor compartment after bulkhead. Using the electric cables to connect the power source to the main motor and the shaft, an additional watertight bulkhead could be installed between the "motor room" and the turbine room. Thus a flooding casualty would be restricted to a small compartment forward of the aftmost portion of the pressure hull.

In the case of the mechanical baseline ship, the reactor compartment bulkhead is 154 feet aft of the forward perpendicular and the aft most point of the pressure is 256 feet from the forward perpendicular. Consider the case of the DCDD electric drive system. The ship service and propulsion turbines and generators require thirty five to forty feet of ship length to arrange. Thus the maximum moment arm (relative to the forward perpendicular) would be on the order of 180 to 190 feet as opposed to nearly 250 feet. This represents a 25 to 30 percent reduction in the unbalanced moment for the same weight of water flooded aboard. Additionally, the smaller compartment limits the total volume that can be flooded to about 40 percent of what could be flooded in the mechanical baseline. These two effects significantly reduce the impact of the flooding and enhance the survivability of the hull. The only question is whether or not such a design would be feasible.

According to [9], the propulsion machinery (including the condensing systems) comprise about twenty two percent of the W2/W3 weight. For the mechanical baseline, not including 72 LTons for the reduction gears, the propulsion machinery weight is 228.5 LTons with an LCG of 220 feet. Using this data, the DCDD can be adjusted for moving the turbines and generators to the new location aft of the reactor compartment. The new bulkhead is estimated as a 1.5 inch thick steel circular plate located at 195 feet aft of the forward perpendicular. Table 7.6 summarizes the changes to the DCDD weight breakdown.

Table 7.5 Alternative Arrangement Option Weight and Moment Summary

	WEIGHT (LTONS)	LCG (FEET)	VCG (FEET)
D.C. Direct Drive Optional Arrangement :			
Weight Group 2/3	1406.4	165.5	14.7
Propulsion Equip.-Unmodified Position	228.5	220.0	18.0
Propulsion Equip.-Modified Position	228.5	180.0	18.0
New Bulkhead	22.5	195.0	16.0
New Weight Group 2/3	1406.4	159.0	14.7
Condition A-1	4202.3	142.9	15.3
Total Lead	350.2	156.7	13.0
Stability Lead	75.3	207.5	2.0
Margin Lead	274.9	142.8	16.0

The lead solution is feasible. The stability lead is driven aft by the shift of nearly 230 LTons forty feet forward. The margin lead is now only 6.5% of the Condition A-1 weight. In practical application, this concept is more suitable for a "clean sheet of paper" design than for a backfit in order to assure adequate future growth margin. However, the equipment fits in the hull, the weight and buoyancy balance works and the lead solution is feasible. Therefore, the design concept is potentially feasible.

Another advantage of this type of arrangement is that the steam system is also restricted to the new, small compartment. Steam at pressures suitable for marine propulsion applications, poses another significant potential hazard to ship safety. In the mechanical variant, the entire length of the ship aft of the reactor compartment is exposed to main steam headers as they run to the turbine steam inlets. Besides reducing the amount of the ship that is exposed to this piping, the moving of the steam system forward reduces the number of piping junctions, unions and drain taps that can fail inadvertently or if the ship is exposed to a sudden shock.

Chapter Eight: Final Conclusions and Recommendations for Further Study

8.1 Conclusions

This study was conducted in an effort to try and answer two key questions. First and foremost, the question is "Can a reasonable electric transmission based propulsion system be built into a submarine?". As demonstrated in Chapters Four through Seven,the answer to this question is yes. The necessary components can be designed, sized and packaged so that electric drive is feasible on a submarine.

The second and far more difficult question to answer is "Why install electric drive as opposed to conventional, mechanical drive propulsion plants?". Here, the answer is not as clear cut.

Electric Drive Advantages

Electric drive does provide a degree of flexibility in arranging the propulsion plant that does not exist for the mechanically based system. The decoupling of the steam system from the main shaft permits the repositioning of the steam plant and associated seawater systems into a more isolatable compartment then current designs allow. This isolation of the steam and seawater systems can have a major impact on the ability of the ship to survive a casualty or battle damage by enhancing the ability of the crew to combat the damage and by limiting the extent of the damage to a smaller portion of the ship. Additionally, the free surface effect of the flooding is significantly reduced.

Electric drive is inherently compatible with a remote propulsion plant operation schemes. The potential exists for the operation of the propulsion plant from a safe haven outside the engineering spaces.

The elimination of the reduction gears coupling the propulsion turbines together eliminates propulsion limitations caused by freewheeling an inoperative turbine. For example,

a mechanically failed turbine would not need to be physically decoupled from the gear train to restore operation.

Electric drive provides the possibility of backing up main propulsion with a ship service electric power source.

The use of electric drive provides the potential to divert the propulsion power of the ship to some combat system related function. For the systems considered here, nearly 20 megawatts of power is directly available. More power could be made available indirectly by "reversing motorizing" the propulsion motor for a short period of time and diverting the ship's kinetic energy to this application.

Electric Drive Disadvantages

Mechanical drive is inherently more efficient by anywhere from 5 to 12 percent (speed averaged). These lower efficiencies increase the fuel load requirements (and increase the costs associated with loading more fuel) and force the restructuring of the operational tempo of the ship.

Electric drive systems are heavier than the mechanical system for the same horsepower. Significant additional weight would be required to provide speed margin if required. Operation of electric motors in excess of the designed rating leads to rapid degradation of the motor's performance and possible motor failure.

Although alternative uses for the propulsion derived electric power (such as advanced combat systems or extremely high power sensors) appear very attractive, submarine operations and the submarine's operating environment do not lend themselves well to such concepts. The inherent covertness required of submarine operations would usually preclude the use of very high powered acoustic sensors and the physics of the deep ocean makes use of electromagnetic systems a very difficult problem not likely to be solved in the near term.

Gear reduced motors are a better option from a weight and efficiency perspective than direct drive motors. It is questionable,however, whether any advantage exists in removing one large gear box only to replace it with another, albeit smaller, one.

As discussed in earlier chapters, surface ship designs derive almost all of the benefits attributed to electric drive from indirect impacts of the use of electric drive in conjunction with gas turbines. The smaller or more optimally arranged surface ship hulls that can be designed for the same payload when using an electric drive system have no parallel in submarine design . For submarine electric propulsion to have a viable future, a requirement for the installation must be found. Possible examples of such a requirement are enhanced ship safety or a use for 20 megawatts of short duty cycle power. Whatever the reason, it must be sufficient to justify the substantial investment needed to develop the mature technology and to absorb the degraded propulsive efficiency.

8.2 Recommendations for Further Work

As discussed in Chapter Five, further work should be done in refining the design of the motors for off-design-point efficiency. Several techniques were offered, but the list is surely not all inclusive.

The use of homopolar motors and the design optimization of them should be explored. NaK is not a good material to use in ship immersed in seawater. Superconducting motor designs should be investigated for their impact on the design of a submarine. Of particular concern would be the shock response of the cryogenics (if required) and the performance of the motor if the cryogenic plant failed.

Good "rule of thumb" weight and volume submarine design parametrics shouldbe to be developed for the various electric drive alternatives. Providing electric drive as an easy option for the submarine designer to consider in a feasibility study will encourage exploration of electric drive as a means to solve problems.

Appendices

Appendix A Efficiency and Volume Weighting Factor Derivation

1. In the definition of the Effective Weight objective function, the factors k_η and k_v were used to relate the effect of marginal changes in efficiency (η) and motor volume (v) on the weight of the submarine's propulsion plant. The purpose of this appendix is to derive the values of the marginal weight factors and discuss their possible improvement for further study.

2. Efficiency Factors. The power delivered to the shaft of a submarine (SHP) by the ship's propulsion plant can be given as

$$SHP = (\text{Reactor Thermal Power})\eta_{mech}\eta_{thermal}\eta_{electric}$$

In actual design practice, the first three factors are essentially constants once the basic technology types are specified(eg., Pressurized water reactor based steam plant). Let the product of the first three terms be K1. Weight Group 2 variations can be thought of as variations resulting directly from variations in the main motor, ie

$$\Delta W_2 = \Delta\text{Motor Weight}$$

and

$$W_2 = f(SHP)$$

By use of a Taylor's series expansion

$$W_2 \approx W_2(SHP = 25{,}000\text{ HP}) + \frac{\partial f}{\partial \eta_e}(1 - \eta_{el}) + \frac{\partial f}{\partial v}v$$

The partial derivative chain rule permits evaluating the efficiency derivative using the SHP equation above (equal to K1) and the derivative of the weight of the propulsion plant with respect to the installed shaft horsepower. Using the parametric relation from [9], W_2 (in units of pounds) can be expressed as

$$W_2 = k \frac{(SHP)}{(\log (SHP))^5}$$

$$\text{where } k = 2.0 \times 10^5$$

Therefore, the incremental change in W_2 per megawatt of shaft horsepower is approximately 40 long tons. A 1 percent delta in motor efficiency implies that the thermal power output must increase by approximately 300 HP or .23 MW in order to provide the same 25,000 shaft horsepower. This correlates to a nine ton per percent efficiency margin factor in Weight Group 2 which corresponds to approximately 12 long tons per percent efficiency for the submerged ship displacement. Therefore, a value for k_η of 12,000 kilograms per percent was used in the various syntheses and analyses.

3. Volume Factors. For volume effects, it was assumed that a one cubic meter increase in motor volume would increase the required volume of the pressure hull by one cubic meter. This corresponds to an increase in ship's displacement of 1,000 liters or 1,000 kilograms (approximately for seawater) per cubic meter of motor volume increase.

4. Improvements. No sensitivity analysis was done to investigate how the synthesized motors would respond to variation of these margin factors. Davis [1] stated that increasing k_η improved the general efficiency of the motors for minimal increase in weight. It is conceivable, however, that gross values of these factors could overwhelm the motor weight and obtain motors with excessive weight and inertia but good efficiency.

Appendix B The Ship Weight Breakdown System (SWBS)

1. The SWBS is the current method of tabulating and controlling the weight of U.S. Navy ships. For submarine application, the SWBS categorizes five conditions that will characterize the ship. These are:

Condition A-1:	The as-constructed weight of the unballasted submarine
Condition A:	The weight of the as-constructed submarine after lead ballast is added to provide stability and margin weight
Normal Surfaced Condition:	The weight of the ballasted submarine with variable loads such as food, weapons and people on board, but with the main ballast tanks empty of water. (also called NSC)
Submerged Displacement:	The weight of water displaced by the fully submerged submarine or NSC plus the weight of water that fills the main ballast tanks when submerged.
Envelope Displacement	The weight of water that would be displaced if the outer envelope of the submarine displaced the water. This differs from the submerged displacement by the amount of water that freely communicates with the sea, the so-called free flood volumes.

2. Condition A-1

This is the weight of construction materials and components that are used in the building of the submarine. The weights are organized by usage into seven numbered primary groups. The primary groups are:

Weight Group 1 (W1):	Weight of material used for the ship's structure and hull.
Weight Group 2 (W2):	Weight of the material and system components used in the ships main propulsion system.
Weight Group 3 (W3):	Weight of the material and system components used in the ship's electrical generation and distribution systems. However, systems or components that might be dedicated to an electric propulsion system would be in W2.
Weight Group 4 (W4):	Weight of the components used in the ship's search, localization and weapons targeting combat systems. This can include water loaded into the submarine's sonar dome.
Weight Group 5 (W5):	Weight of the ship's non-propulsion plant based engineering systems such as atmosphere regeneration and control, ventilation, hydraulics and air systems.
Weight Group 6 (W6):	Weight of outfitting and furnishings used to make the ship "livable".
Weight Group 7 (W7):	Weight of the systems used to support and deliver the ship's weapons. This is as opposed to W4 which aims the weapons and "Variable Loads" discussed later which includes the weight of the weapons.

Each weight group is broken down to subgroupings that more closely identify the components/systems involved. For example, W23 may be all propulsion electric equipment, W235 may be propulsion motor electric systems and W2355 may be the main motor switchgear. As a ship design matures, the level of specificity of the weight groups grow until at Detailed Design, every, individual component on the submarine is accounted for.

Condition A-1 is the sum of the seven weight groups, ie.

$$\text{Condition A-1} = \sum_{1}^{7} (Wi)$$

3. Condition A

Condition A is the weight of the as constructed submarine including the weight of fixed lead ballast. Condition A can be thought of as the finished, end of construction weight of the submarine, before any people, weapons, food or other payload type items are loaded aboard.

3.1 Lead

In the design of a submarine, lead is planned for and then loaded during the construction period for two basic reasons. Stability lead is loaded on to the ship to balance any longitudinal moment that might occur due to the arrangement of the equipment in the seven primary weight groups. Since a submarine operates fully submerged, there is no natural righting of the ship due to the free surface of the ocean as there is with a surface vessel. Therefore, any unbalanced moment on the ship will result in a permanent angle on the ship. The stability lead is positioned to alleviate this. Additionally, since submarines are essentially bodies of revolution, there is nothing in the geometry of the hull to ensure the ship has a natural tendency to remain in an upright condition. By elementary hydrostatics, it can be shown that the buoyant forces associated with the water weight displaced by the submarine hull act at the radial centroid of the body of revolution. The stability lead is loaded so that the vertical center of gravity of the ship is at least one foot lower in the hull than the vertical center of buoyancy.

By doing this, the designer ensures that a moment is generated whenever the ship rolls about its longitudinal axis that tends to return the ship to an upright condition. This "righting moment" is caused by the physical motion of the center of gravity about the center of buoyancy. The separation of the two centers of action form a "righting arm" that the forces of buoyancy and gravity act upon to right the ship. A good rule of thumb is that stability lead should generally not be more than 20% of the total lead ballast.

The second purpose for lead is to provide weight margin. The margin permits the natural maturing of the design to be accounted for over the period of design to ship delivery. It also permits weight growth associated with system improvements over the course of ship life to be absorbed without having to modify the ship's hull. The weight that a submarine can float is limited by the weight of water its hull displaces. Therefore, margin is required if the ship is to change in any significant manner over the course of its twenty to thirty year lifetime.

4. Normal Surface Condition

Normal Surface Condition (NSC) is the nominal weight of water displaced by the deployed submarine on the surface. NSC is the sum of Condition A and the weight of payload items or variable loads that the ship carries to sea.

4.1 Variable Loads

Variable loads are just that: load items whose weight over the course of time is not constant. For example, when a torpedo is expended, the ship is lighter by the weight of that weapon. Other items are fuel oil and lubricating/hydraulic oils, foodstuffs, spare parts, personnel and their gear, and atmosphere control/regeneration supplies. Since the buoyancy of the ship is fixed, changes in variable loads are compensated for continually by moving variable ballast water between tanks in the ship (variable ballast or "trim" tanks). Water can be brought in to the ship or pumped out as required to maintain the ship neutrally buoyant and trimmed. A nominal amount of variable ballast water is included in the variable loads.

5. Submerged Displacement

The submerged displacement of the ship is the weight required for the ship to be neutrally buoyant when submerged. In other words, submerged displacement equals the weight of the water displaced by the complete immersion of the submarine hull. In practical terms, it is the sum of the weight of the ship in NSC and the weight of the water in the completely filled Main Ballast Tanks.

5.1 Main Ballast Tanks

The Main Ballast Tanks are large tanks,external to the pressure that fill with water to provide the additional weight required to submerge the ship and make it neutrally buoyant. They serve the additional purpose of providing rapid buoyancy when the ship is surfacing normally or in response to a casualty. For this reason, the weight of the water in the MBT's is often referred to as "reserve buoyancy".

6. Envelope Displacement

In addition to the above, there are "nooks and crannies" in the submarine exterior hull that are not water tight and are referred to as "free flood". This free flood weight is accounted for in the envelope displacement because when the speed and powering calculations are done, the weight of the water in the free flood areas is also being driven by the power plant. Therefore, the submerged speed attained is a function of the envelope displacement.

Appendix C Synchronous Machine Design and Efficiency Programs

1. General Comments

The programs presented herein were all compiled using Version 5.1 of the Microsoft C compiler and were run on an 8 MHz IBM PC XT clone with an Intel 8087 math/floating point coprocessor. The code was ported to a Macintosh personal computer and compiled using Version 3.0 Think's Lightspeed C by Symantec Corporation. Except for the functions specific to this study presented in the program listings below, standard library calls were used to minimize conflicts when porting the code to other environments.

Variables appearing in all uppercase letters are constants and are defined only in the header file, def.h, that must appear in the same directory as the code when compiling. A listing of def.h is included in this appendix.

2. General Synchronous Design Code: syn.c

syn.c is the initial synthesis program used in Chapter Four of the study report. It is primarily the program developed by Davis [1] for use in his study of surface warship electric propulsion systems. The principle difference is that the code presented here provides an upper limit to the value of the rotor current density. The program runs fairly quickly, but is subject to "locking" on to local minima and the results are not always self consistent electrically. The program is very self consistent in determining the physical dimensions of the machines (weight, volume, diameter, length, etc.) and is also consistent with the dimensional results of the later version of the design code presented in the next paragraph. Additionally, in some input design types, the limit on the maximum rotor current density is particularly challenging to meet and the program converges to results that have unacceptablly low values of synchronous reactance. In those cases or in cases where more than the weight/volume characteristics of the motor are needed, the designer should consider the second code presented here. If only the size and weight are needed, such as for an initial feasibility ship design, this code is adequate.

2.1 Input Data File: syn.dat

The input data file structure for syn.c is:

<u>SYN.DAT FORMAT</u>

seed:	The random number generator seed value.
p:	The desired number of pole pairs for this design.
minpwr:	The desired rated output power of the motor in HP.
ke:	The W2 efficiency weighting factor.
kv:	The W2 volume weighting factor.
rpm:	The desired motor rpm at rated power.

A sample syn.dat would be:

```
6
5
25000.0
12000.0
1000.0
120.0
```

This would generate a design with 6 as the seed, 10 poles (5 pole pairs), 25,000 HP at 120 rpm.

2.2 syn.c Program Listing

```
#include "stdio.h"
#include "def.h"
#include "math.h"
#include "float.h"
/*  program name:  syn.c for synchronous, round rotor machines */

long int seed;                /* start point for random number generator */
double b[26][26], h[11][26], ks[8], kr[8];
      /* b is "best" array, h is "hold" array, ks/kr are winding factors */

main()
{
double design_point(), rnd_walk(), swf(), rwf(), ke, kv, minpwr,
      stepsize, random(), freq, rpm;
int p, iteration, i, j, best, print_out(), loops;
FILE *fopen(), *fp;

printf("\nReading input data from SYN.DAT . . .");
```

```
fp=fopen("syn.dat","r");       /* input seed for random numbers */
fscanf(fp,"%d",&seed);fscanf(fp, "%d", &p);     /* input number of pole
pairs */
fscanf(fp, "%lf", &minpwr);    /* input machine power, derived fm ASSET */
minpwr*=746.0;                 /* convert to watts */
fscanf(fp, "%lf", &ke);        /* CERs for Effective Weight */
fscanf(fp, "%lf", &kv);
fscanf(fp, "%lf", &rpm);             /* machine max shaft rpm  */
fclose(fp);
 /*
printf("\nHow many loops do you want? ");
scanf("%d", &loops);  */
loops = 25;
printf("\n\nDoing program calculations . . .\n");

for (i=1; i < 8; i+=2)               /* harmonic winding factors   */
      {
      ks[i]=swf(i);
      kr[i]=rwf(i);
}

freq=rpm*p/60.0;               /* max electrical frequency */

/*  MAIN BODY OF THE PROGRAM */

for (i=1; i <= loops; ++i)
      {
      stepsize=0.1;
      iteration=0;
      design_point(minpwr, p, ke, kv, freq);
                               /* put stuff in the hold array */
      while (iteration <= 10)
            {
            rnd_walk(minpwr, p, stepsize, ke, kv, freq);
                               /* stagger around */
            best=0;                  /* index to best EW of the lot */
            for (j=1; j<=10; ++j)
                  if (h[j][18] < h[best][18])
                        best=j;           /* find the best machine */
            if (fabs((h[0][18] - h[best][18])/h[0][18]) < 0.005)
                               /* small improvement in EW */
                  {
                  stepsize/=2.0;
                  ++iteration;
                  }
            else               /* transfers best to 0 position */
                  {
                  for (j=1; j <= 25; ++j)
                        h[0][j] = h[best][j];
                  }
            }
      for (j=1; j <= 25; ++j)
            b[i][j]=h[best][j];            /* keep the best machine */
      }

best=1;
```

```
for (i=1; i <= loops; ++i)
      if (b[i][18] < b[best][18])
            best=i;            /* find and keep the best of the best */
minpwr/=746.0;                             /* turn back into hp */

print_out(best, p, minpwr, ke, kv, rpm);  /* output to disk file */

fp=fopen("syn.dat","w");                  /* output seed */
fprintf(fp,"%d", seed);
fprintf(fp,"\n%d", p);
fprintf(fp,"\n%lf", minpwr);
fprintf(fp,"\n%lf", ke);
fprintf(fp,"\n%lf", kv);
fprintf(fp,"\n%lf", rpm);
fclose(fp);
}
/*  END OF MAIN PROGRAM; ALL THAT FOLLOW ARE FUNCTIONS */

double design_point(minpwr, p, ke, kv, freq)
                         /* determines a random design point */
double minpwr, ke, kv, freq;
int p;
{
double r, jrnl, jr, js, ls, lr, dcore, ds, dr, g, w, l, xs, eaf, i2rr,
      va, ph, pe, i2r, vol, wt, effcy, ew, xs1, xs5, xs7, xsal,
      cw, siv, scv, riv, rcv, loa, doa, wt_iron, find_siv();

extern double  random();
int c=0, d=0;

while (d != 1) {
while (c != 1)                       /*infinite loop*/
      {
      r=random()*RMAX;
      if ((2*PI*r*freq/p) < MAX_TIP_SPEED)  /* check rotor tip speed */
            break;
      }

w=2*PI*freq;
lr=random()*0.5 + 0.25;        /* rotor slot factor */
dr=random()*r/5.0:             /* slot no deeper than 20% of rotor radius */
dcore=(BR*r)/(BSAT*p);         /* back iron depth */
ds=random()*0.9*dcore;         /* slot depth < 90% of body depth */
while (c != 1)                 /* gap dimension */
      {
      g=random()*(0.1*r - GMIN) + GMIN;
            if (g > 0)
                  break;
      }
ls=random()*0.5 + 0.25;        /* stator slot factor */
js=random()*JSMAX;             /* full load stator current density */

jrnl=(BR*g*p)/(8*MU*RSF*r*dr*lr*kr[1]); /* noload rotor current density */
xs1=ks[1]*ks[1];
xs5=(ks[5]*ks[5]/25);
xs7=(ks[7]*ks[7]/49);
xsal=(5*ls*PI*ds/18);
```

```
xs=(MU*js*SSF*(r+g)*(r+g)*ds*PI*ls * (12*(xs1 + xs5 + xs7)/(PI*g*p) +
xsal))
                  /(12*r*BR*ks[1]);
                                    /* p.u. synch impedance */
if (xs > 2.0)
      continue;                     /* don't want xs too big */

eaf=sqrt(1 + xs*xs + 2*xs*0.6); /* 0.6 is sin(Á), pwr factor angle,
      eaf is p.u. internal voltage at full load */

jr=eaf*jrnl;                              /* jr full load, linear with eaf */

while(jr>JRMAX + 1.)  {
      g*=(JRMAX/jr);
      if (g < GMIN)
            break;          /*can't solve this geometry
                        with jr and g in specification;
                        this loop breaks to the end of
                        the jr loop and then loops back
                        to the reinitialization steps*/

      jrnl=(BR*g*p)/(8*MU*RSF*r*dr*lr*kr[1]);
      xs=(MU*js*SSF*(r+g)*(r+g)*ds*PI*ls * (12*(xs1 + xs5 + xs7)
                        /(PI*g*p) + xsal))/(12*r*BR*ks[1]);
                              /* p.u. synch impedance */
      if (xs > 2.0)
            break;  /* don't want xs too big; this will break out
                  of the loop and the first statement after
            the bracket will reinitiate the entire process */

      eaf=sqrt(1 + xs*xs + 2*xs*0.6);
                  /* 0.6 is sin(Á), pwr factor angle,
                  eaf is p.u. internal voltage at full load */
      jr=eaf*jrnl;

}
if (g < GMIN)
      continue;
if (xs > 2.0)
      continue;
else
      ++d;

l=(minpwr*p)/(2*BR*w*ks[1]*r*SSF*ds*PI*(r+g)*ls*js*PF);  /* active length
*/

va=2*PI*r*l*w*BR*ks[1]*js*SSF*(r+g)*ds*ls/p;    /* va rating */

siv = find_siv(l, r, g, ds, dcore, ls);         /* stator iron volume */
riv = l*PI*r*(r - 2*dr*lr);               /* rotor iron volume */
scv = 2*PI*(r+g)*ds*ls*(l + 2.3094*PI*(r+g)*CP/p);
                                    /* stator copper volume */
rcv = 2*PI*r*dr*lr*(l + 2.3094*PI*r/p);         /* rotor copper volume */
cw = (rcv + scv)*DCU;                     /* total copper weight */
loa = l + 4*(r+g);                        /* length-over-all */
doa = 2*(r+g+ds+dcore);                   /* over-all-diameter */
vol = VOLALL*(loa*PI*doa*doa/4);          /* machine envelope volume */
```

```
wt = WTALL*(cw + D*(BRNGS*riv + siv));          /* machine weight in kg */
wt_iron = D*(riv + siv);                     /* iron weight only */

ph = 31.86225*BETA*freq*BR1*HC1*wt_iron/D;
      /* hysteresis loss in watts, uses iron weight of machine */

pe = (106236.9*NU*BSAT*BSAT*T1*T1*freq*freq*wt_iron)/(RHO*D);
      /* eddy current loss in watts, uses iron weight of machine */

i2r = 2.0*SSF*ds*CRHO*PI* (1 + 2.3094*PI*(r+g)*CP/p) *js*js*(r+g)*ls;
                              /* stator copper loss in watts */
                                    /* revised 1-12-87 */

i2rr = 2.0*RSF*dr*r*lr*jr*jr*CRHO*PI* (1 + 2.3094*PI*r/p);
                        /* rotor excitation losses, 1-12-87 */
i2r+=i2rr;              /* total copper losses */


effcy=(minpwr)/(minpwr + ph + pe + i2r);

ew=wt + ke*(1-effcy) + kv*vol;                    /* Effective weight */

h[0][1]=js;     h[0][2]=freq;   h[0][3]=w;      h[0][4]=r;      h[0][5]=g;
h[0][6]=dcore;  h[0][7]=ds;     h[0][8]=dr;     h[0][9]=ls;     h[0][10]=lr;
h[0][11]=vol;   h[0][12]=wt;    h[0][13]=ph;    h[0][14]=pe;    h[0][15]=i2r;
h[0][16]=va;    h[0][17]=effcy; h[0][18]=ew;    h[0][19]=l;     h[0][20]=jr;
h[0][21]=jrnl;  h[0][22]=xs;    h[0][23]=eaf;   h[0][24]=loa;   h[0][25]=doa;

      /* this section just changed all the variables in the "hold" array */

return;
}}
double rnd_walk(minpwr, p, stepsize, ke, kv, freq)
                  /* walks about design_point 10 times */
      double stepsize, minpwr, ke, kv, freq;
      int p;
{
double r, jrnl, jr, js, ls, lr, dcore, ds, dr, g, w, l, xs, eaf, i2rr,
      va, ph, pe, i2r, vol, wt, effcy, ew, xs1, xs5, xs7, xsal,
      cw, siv, scv, riv, rcv, loa, doa, wt_iron, find_siv();
extern double random();
int i=1,j=0;
while (i <= 10)
      {
      /* read in the walk around the design point */

      js=h[0][1]*(1 + stepsize*(random() - 0.5));
      if (js > JSMAX)
            js = JSMAX;       /* reset to limit */
      w=2*PI*freq;
      r=h[0][4]*(1 + stepsize*(random() - 0.5));
      if ((w*r/p) > MAX_TIP_SPEED)
            continue;         /* go to next try if violated */
      g=h[0][5]*(1 + stepsize*(random() - 0.5));
            if (g < GMIN)
                  g=GMIN;           /* reset to the limit */
```

```
        dcore=(BR*r)/(BSAT*p);          /* most efficient use of iron */
        ds=h[0][7]*(1 + stepsize*(random() - 0.5));
              if (ds > dcore)           /* can't have too-deep slots */
                    ds=dcore;    /* reset to the limit */
        dr=h[0][8]*(1 + stepsize*(random() - 0.5));
        ls=h[0][9]*(1 + stepsize*(random() - 0.5));
              if (ls > 0.75)
                    ls=0.75;     /* reset to the limit */
              if (ls < 0.25)
                    ls=0.25;
        lr=h[0][10]*(1 + stepsize*(random() - 0.5));
              if (lr > 0.75)
                    lr=0.75;     /* reset to the limit */
              if (lr < 0.25)
                    lr=0.25;

        /* compucation section of the walk */
  jnl=(BR*g*p)/(8*MU*RSF*r*dr*lr*kr[1]); /* noload rotor current density */

  xs1=ks[1]*ks[1];
  xs5=(ks[5]*ks[5]/25);
  xs7=(ks[7]*ks[7]/49);
  xsal=(5*ls*PI*ds/18);
  xs=(MU*js*SSF*(r+g)*(r+g)*ds*PI*ls *  (12*(xs1 + xs5 + xs7)/(PI*g*p) +
  xsal))
                  /(12*r*BR*ks[1]);
                              /* p.u. synch impedance */
  if (xs > 2.0)
        continue;             /* can't have xs too big */

  eaf=sqrt(1 + xs*xs + 2*xs*0.6);     /* 0.6 is sin(Á), pwr factor angle,
                          eaf is p.u. internal voltage at full load */

  jr=eaf*jrnl;    /* jr full load, linear with eaf */

  while(jr>(JRMAX+1.))   {
        g*=(JRMAX/jr);
        if (g < GMIN) {
              j++;
              printf("\nj = %d,jr = %lf, g = %lf\n",j,jr,g);
              break;           /*can't solve this geometry
                          with jr and g in specification;
                          this loop breaks to the end of
                          the jr loop and then loops back
                          to the reinitialization steps*/
        }
        jrnl=(BR*g*p)/(8*MU*RSF*r*dr*lr*kr[1]);
        xs=(MU*js*SSF*(r+g)*(r+g)*ds*PI*ls *  (12*(xs1 + xs5 + xs7)
                          /(PI*g*p) + xsal))/(12*r*BR*ks[1]);
                              /* p.u. synch impedance */
        if (xs > 2.0)
              break;  /* don't want xs too big; this will break out
              of the loop and the first statement after
                    the bracket will reinitiate the entire process */

        eaf=sqrt(1 + xs*xs + 2*xs*0.6);
                    /* 0.6 is sin(Á), pwr factor angle,
```

```
            eaf is p.u. internal voltage at full load */
      jr=eaf*jrnl;

}
if (g < GMIN)
      continue;
if (xs > 2.0)
      continue;

l=(minpwr*p)/(2*BR*w*ks[1]*r*SSF*ds*PI*(r+g)*ls*js*PF);  /* active length
*/

va=2*PI*r*l*w*BR*ks[1]*js*SSF*(r+g)*ds*ls/p;    /* va rating */

siv = find_siv(l, r, g, ds, dcore, ls);   /* stator iron volume */
riv = l*PI*r*(r - 2*dr*lr);               /* rotor iron volume */
scv = 2*PI*(r+g)*ds*ls*(1 + 2.3094*PI*(r+g)*CP/p);
                                  /* stator copper volume */
rcv = 2*PI*r*dr*lr*(1 + 2.3094*PI*r/p);         /* rotor copper volume */
cw = (rcv + scv)*DCU;                     /* total copper weight */
loa = l + 4*(r+g);                        /* length-over-all */
doa = 2*(r+g+ds+dcore);                   /* over-all-diameter */
vol = VOLALL*(loa*PI*doa*doa/4);          /* machine envelope volume */

wt = WTALL*(cw + D*(BRNGS*riv + siv));          /* machine weight in kg */
wt_iron = D*(riv + siv);                  /* iron weight only */

ph = 31.86225*BETA*freq*BR1*HC1*wt_iron/D;
      /* hysteresis loss in watts, uses iron weight of machine */

pe = (106236.9*NU*BSAT*BSAT*T1*T1*freq*freq*wt_iron)/(RHO*D);
      /* eddy current loss in watts, uses iron weight of machine */

i2r = 2.0*SSF*ds*CRHO*PI* (1 + 2.3094*PI*(r+g)*CP/p) *js*js*(r+g)*ls;
                              /* stator copper loss in watts */
                                  /* revised 1-12-87  */

i2rr = 2.0*RSF*dr*r*lr*jr*jr*CRHO*PI* (1 + 2.3094*PI*r/p);
                          /* rotor excitation losses, 1-12-87 */
i2r+=i2rr;                /* total copper losses */

effcy=(minpwr)/(minpwr + ph + pe + i2r);

ew=wt + ke*(1-effcy) + kv*vol;                     /* Effective weight */

h[i][1]=js;     h[i][2]=freq;    h[i][3]=w;      h[i][4]=r;      h[i][5]=g;
h[i][6]=dcore;  h[i][7]=ds;      h[i][8]=dr;     h[i][9]=ls;     h[i][10]=lr;
h[i][11]=vol;   h[i][12]=wt;     h[i][13]=ph;    h[i][14]=pe;    h[i][15]=i2r;
h[i][16]=va;    h[i][17]=effcy;  h[i][18]=ew;    h[i][19]=l;     h[i][20]=jr;
h[i][21]=jrnl;  h[i][22]=xs;     h[i][23]=eaf;   h[i][24]=loa;   h[i][25]=doa;

      /* this section just changed all the variables in the "hold" array */
      ++i;              /* go to the next h[i][] */
      }

return;
}
```

```
print_out(best, p, minpwr, ke, kv, rpm)
      int best, p;
      double minpwr, ke, kv, rpm;
{
char outfile[14];
FILE *fpo, *fopen();
int i;
/*
printf("\nWhat is the name of the file where you want the output? ");
scanf("%s", outfile);   */

fpo=fopen("syn.out", "w");


fprintf(fpo,"%d", p);
fprintf(fpo,"\n%lf", minpwr);
fprintf(fpo,"\n%lf", ke);
fprintf(fpo,"\n%lf", kv);
fprintf(fpo,"\n%lf", rpm);
for (i=1; i <= 25; ++i)
      fprintf(fpo,"\n%lf",b[best][i]);
fprintf(fpo, "\n");
fclose(fpo);
}
double find_siv(l, r, g, ds, dcore, ls)
      double l, r, g, ds, dcore, ls;
{
double one, two, three, four;

one = (r+g+ds+dcore)*(r+g+ds+dcore) - (r+g)*(r+g);
two = 2*PI*(r+g)*ds*ls;
three = (r+g+ds+dcore)*(r+g+ds+dcore) - (r+g+ds)*(r+g+ds);

four = l*(PI*one - two) + PI*4*(r+g)*three;
return(four);
}
#define   MULTIPLIER   25173
#define   MODULUS      32768
#define   INCREMENT    13849
#define   MODFLT      32768.0
double random()
{
      extern long int seed;
      seed=(MULTIPLIER*seed+INCREMENT) % MODULUS;
      return(seed/MODFLT);
}
double swf(n)           /* stator winding factor */
      int n;          /* harmonic order */
      {
      double kp, kb;

      kp=cos(0.3142*n);       /* pitch factor, assumes 0.8 coil pitch */
      kb=(sin(0 5236*n))/(0.5236*n);           /* breadth factor, from
              Kirtley's "Basic Formulas ... " and assumes an
```

```
                    electrical winding angle of 60° */
        return(kp*kb);
 }
double rwf(n)            /* rotor winding factor, same comments as swf() */
        int n;
{
        double kp, kb;
        kp=1;
        kb=(sin(0.5236*n))/(0.5236*n);
        return(kp*kb);
        }
```

3. Special Synchronous Design Code: synkirt.c

Synkirt.c served two principle needs in the course of the study. The primary goal was to focus in on a method of synthesis that provided more self consistent results than syn.c did for the electrical aspects of the designs. The secondary goal wa to permit the design algorithm to search a wider design variable space without recoding and recompiling each time.

The first goal was attacked by reexamination of the design random variables versus the results of the syntheses. It was noted that the stator current was almost always converging to the maximum value allowed. Additionally, the method by which the design algorithm in syn.c limited the value of the rotor current sometimes led to unreasonable values for the synchronous reactance. In synkirt.c, the stator current is fixed at the maximum value and the synchronous reactance is fixed at a value of 2.0 per unit (normalized value). The rotor current is a random variable and the dimensions of the rotor bar are then calculated to ensure the proper coupling between the stator and the rotor.

The second goal was met by modifying the requirements of the input file to permit the designer to specify the number of times the random walk program "dithers" about the current best design before returning a "best" answer to the main program. In syn.c, this was fixed at 10 times per subroutine call. "npass" can be set anywhere from zero (0) to fifty (50). (Fifty was a limit associated with the available memory of the computer used for this study. The variable could be higher on a more capable machine, but the program would have to be recompiled with new array specifications). The other change was to permit the designer to specify the degree to which the stepsize (the limits of the search space dimensions) changed as small changes in the objective function indicated an impending minimum. "stepshrink" can be set anywhere from zero to unity. In syn.c, this was fixed at a value of 0.5, or one half.

3.1 Input Data File: syn.dat

The input data file is identical to the one for syn.c except for there are two additional entries in this version:

SYN.DAT FORMAT

seed:	The random number generator seed value.
p:	The desired number of pole pairs for this design.
minpwr:	The desired rated output power of the motor in HP.
ke:	The W2 efficiency weighting factor.
kv:	The W2 volume weighting factor.
rpm:	The desired motor rpm at rated power.
stepshrink:	The percent the stepsize will shrink when optimality nears.
npass:	The number of times the random walk subroutine will "loop" the design algorithm before returning an answer.

A sample syn.dat would be:

```
6
5
25000.0
12000.0
1000.0
120.0
0.75
50
```

This would generate a design with 6 as the seed, 10 poles (5 pole pairs), 25,000 HP at 120 rpm.

3.2 synkirt.c Program Listing

```
#include "stdio.h"
#include "def.h"
#include "math.h"
#include "float.h"
            /*  program name:  synkirt.c for synchronous, round rotor
machines */

            /* this varient assumes a constant stator current and
synchronous reactance
            randomizes rotor current, and meshes the physics by calculating
the rotor
            dimensions to fit the values calculated.*/
```

```
            /* syn.dat requires two new entries for this code versus
syn.c*/

            /* stepshrink:  the fractional change in the stepsize as
optimality is
            approached.  syn.c used a fixed 0.5 value*/

            /* npass:  the nnumber of loops through the random walk routine
per
            subroutine call the program makes before returning a best
answer.
            This was fixed at ten (10) in syn.c.*/

long int seed;              /* start point for random number generator */
double b[26][26], h[51][26], ks[8], kr[8];
      /* b is "best" array, h is "hold" array, ks/kr are winding factors */

main()
{
double design_point(), rnd_walk(), swf(), rwf(), ke, kv, minpwr,
      stepsize, random(), freq, rpm, stepshrink;
int p, iteration, i, j, best, print_out(), loops, npass;
FILE *fopen(), *fp;

printf("\nReading input data from SYN.DAT . . .");

fp=fopen("syn.dat","r");      /* input seed for random numbers */
fscanf(fp,"%d",&seed);
fscanf(fp, "%d", &p);         /* input number of pole pairs */
fscanf(fp, "%lf", &minpwr);   /* input machine power, derived fm ASSET */
minpwr*=746.0;                /* convert to watts */
fscanf(fp, "%lf", &ke);       /* CERs for Effective Weight */
fscanf(fp, "%lf", &kv);
fscanf(fp, "%lf", &rpm);        /* machine max shaft rpm  */
fscanf(fp,"%lf",&stepshrink);   /*size change for the step reduction*/
fscanf(fp, "%d", &npass);       /*number of passes used in random_walk
                         iterations; <=50 */
fclose(fp);
 /*
printf("\nHow many loops do you want? ");
scanf("%d", &loops);  */
loops = 25;
printf("\n\nDoing program calculations . . .\n");

for (i=1; i < 8; i+=2)              /* harmonic winding factors   */
      {
      ks[i]=swf(i);
      kr[i]=rwf(i);
      }

freq=rpm*p/60.0;              /* max electrical frequency */

/*  MAIN BODY OF THE PROGRAM */

for (i=1; i <= loops; ++i)
      {
```

```
        stepsize=0.1;
        iteration=0;
        design_point(minpwr, p, ke, kv, freq);
                                /* put stuff in the hold array */
        while (iteration <= 10)
                {
                rnd_walk(minpwr, p, stepsize, ke, kv, freq,npass);
                                /* stagger around */
                best=0;                 /* index to best EW of the lot */
                for (j=1; j<=npass; ++j)
                        if (h[j][18] < h[best][18])
                                best=j;         /* find the best machine */
                if (fabs((h[0][18] - h[best][18])/h[0][18]) < 0.005)
                                /* small improvement in EW */
                        {
                        stepsize*=stepshrink;
                        ++iteration;
                        }
                else                    /* transfers best to 0 position */
                        {
                        for (j=1; j <= 25; ++j)
                                h[0][j] = h[best][j];
                        }
                }
        for (j=1; j <= 25; ++j)
                b[i][j]=h[best][j];             /* keep the best machine */
        }

best=1;
for (i=1; i <= loops; ++i)
        if (b[i][18] < b[best][18])
                best=i;         /* find and keep the best of the best */
minpwr/=746.0;                                  /* turn back into hp */

print_out(best, p, minpwr, ke, kv, rpm);  /* output to disk file */

fp=fopen("syn.dat","w");                        /* output seed */
fprintf(fp,"%d", seed);
fprintf(fp,"\n%d", p);
fprintf(fp,"\n%lf", minpwr);
fprintf(fp,"\n%lf", ke);
fprintf(fp,"\n%lf", kv);
fprintf(fp,"\n%lf", rpm);
fprintf(fp,"\n%lf",stepshrink);
fprintf(fp, "\n%d", npass);
fclose(fp);
}
/*  END OF MAIN PROGRAM; ALL THAT FOLLOW ARE FUNCTIONS */

double design_point(minpwr, p, ke, kv, freq)
                        /* determines a random design point */
double minpwr, ke, kv, freq;
int p;
{
double r, jrnl, jr, js, ls, lr, dcore, ds, dr, g, w, l, xs, eaf, i2rr,
        va, ph, pe, i2r, vol, wt, effcy, ew, xs1, xs5, xs7, xsal,
        cw, siv, scv, riv, rcv, loa, doa, wt_iron, find_siv(),
```

```
          r1,g1,test,xpal;



extern double  random();
int c=0, d=0;

while (d != 1) {
while (c != 1)                          /*infinite loop*/
        {
        r=random()*RMAX;
        if ((2*PI*r*freq/p) < MAX_TIP_SPEED)  /* check rotor tip speed */
                break;
        }
w=2*PI*freq;
lr=random()*0.5 + 0.25;         /* rotor slot factor */
dr=random()*r/5.0;                /* slot no deeper than 20% of rotor radius
*/
        if (dr < .005)
        r=.005;
dcore=(BR*r)/(BSAT*p);          /* back iron depth */
ds=random()*0.9*dcore;          /* slot depth < 90% of body depth */
g=GMIN;                           /* gap dimension */
ls=random()*0.5 + 0.25;           /* stator slot factor */
xs=2.0;                           /* p.u. synch impedance */
eaf=sqrt(1 + xs*xs + 2*xs*0.6); /* 0.6 is sin(Á), pwr factor angle,
        eaf is p.u. internal voltage at full load */

js=JSMAX;
xs1=ks[1]*ks[1];
xs5=(ks[5]*ks[5]/25);
xs7=(ks[7]*ks[7]/49);
xsal=(5*ls*PI*ds/18);
test=1.;
r1=r+g;
while(test>.001)  {
        xpal=12.*BR*r*ks[1]*xs/(MU*js*SSF*ls*ds*r1*r1*PI);
        g1=12.*(xs1 + xs5 + xs7)/p/PI*(1./(xpal-xsal));
        test=fabs(g-g1)/g1;
        g=g1;
        r1=r+g;
        printf("\ntest=%lf,\tg=%lf",test,g);
}
if (g < GMIN)
        continue;
if (xs > 2.0)
        continue;
jrnl=(BR*g*p)/(2*MU*RSF*r*dr*lr*kr[1]); /* noload rotor current density */
printf("\njrnl = %lf",jrnl);
jr=eaf*jrnl;
printf("\njr = %lf",jr);

if (jr > JRMAX)
        continue;
else
        ++d;
```

```
l=(minpwr*p)/(2*BR*w*ks[1]*r*SSF*ds*PI*(r+g)*ls*js*PF);  /* active length
*/

va=2*PI*r*l*w*BR*ks[1]*js*SSF*(r+g)*ds*ls/p;     /* va rating */

siv = find_siv(l, r, g, ds, dcore, ls);          /* stator iron volume */
riv = l*PI*r*(r - 2*dr*lr);               /* rotor iron volume */
scv = 2*PI*(r+g)*ds*ls*(l + 2.3094*PI*(r+g)*CP/p);
                                        /* stator copper volume */
rcv = 2*PI*r*dr*lr*(l + 2.3094*PI*r/p);          /* rotor copper volume */
cw = (rcv + scv)*DCU;                     /* total copper weight */
loa = l + 4*(r+g);                        /* length-over-all */
doa = 2*(r+g+ds+dcore);                   /* over-all-diameter */
vol = VOLALL*(loa*PI*doa*doa/4);          /* machine envelope volume */

wt = WTALL*(cw + D*(BRNGS*riv + siv));           /* machine weight in kg */
wt_iron = D*(riv + siv);                  /* iron weight only */

ph = 31.86225*BETA*freq*BR1*HC1*wt_iron/D;
      /* hysteresis loss in watts, uses iron weight of machine */

pe = (106236.9*NU*BSAT*BSAT*T1*T1*freq*freq*wt_iron)/(RHO*D);
      /* eddy current loss in watts, uses iron weight of machine */

i2r = 2.0*SSF*ds*CRHO*PI* (l + 2.3094*PI*(r+g)*CP/p) *js*js*(r+g)*ls;
                              /* stator copper loss in watts */
                                  /* revised 1-12-87 */

i2rr = 2.0*RSF*dr*r*lr*jr*jr*CRHO*PI* (l + 2.3094*PI*r/p);
                          /* rotor excitation losses, 1-12-87 */
i2r+=i2rr;                /* total copper losses */


effcy=(minpwr)/(minpwr + ph + pe + i2r);

ew=wt + ke*(l-effcy) + kv*vol;                   /* Effective weight */

h[0][1]=js;      h[0][2]=freq;    h[0][3]=w;      h[0][4]=r;      h[0][5]=g;
h[0][6]=dcore;   h[0][7]=ds;      h[0][8]=dr;     h[0][9]=ls;     h[0][10]=lr;
h[0][11]=vol;    h[0][12]=wt;     h[0][13]=ph;    h[0][14]=pe;    h[0][15]=i2r;
h[0][16]=va;     h[0][17]=effcy;  h[0][18]=ew;    h[0][19]=l;     h[0][20]=jr;
h[0][21]=jrnl;   h[0][22]=xs;     h[0][23]=eaf;   h[0][24]=loa;   h[0][25]=doa;
      /* this section just changed all the variables in the "hold" array */
return;
}}


double rnd_walk(minpwr, p, stepsize, ke, kv, freq, npass)
                /* walks about design_point 10 times */
      double stepsize, minpwr, ke, kv, freq;
      int p, npass;
{
double r, jrnl, jr, js, ls, lr, dcore, ds, dr, g, w, l, xs, eaf, i2rr,
      va, ph, pe, i2r, vol, wt, effcy, ew, xsl, xs5, xs7, xsal,
      cw, siv, scv, riv, rcv, loa, doa, wt_iron, find_siv(),rl,
```

```
	g1,test,xpal;
extern double random();
int i=1,j=0;

js=JSMAX;
while (i <= npass)
	{
	/* read in the walk around the design point */

	w=2*PI*freq;
	r=h[0][4]*(1 + stepsize*(random() - 0.5));
	if ((w*r/p) > MAX_TIP_SPEED)
		continue;		/* go to next try if violated */
	dcore=(BR*r)/(BSAT*p);		/* most efficient use of iron */
	ds=h[0][7]*(1 + stepsize*(random() - 0.5));
		if (ds > dcore)		/* can't have too-deep slots */
			ds=dcore;	/* reset to the limit */
	dr=h[0][8]*(1 + stepsize*(random() - 0.5));
	if (dr < 0.005)
		dr=.005;  /*reasonable fabrication limits*/
	ls=h[0][9]*(1 + stepsize*(random() - 0.5));
		if (ls > 0.75)
			ls=0.75;	/* reset to the limit */
		if (ls < 0.25)
			ls=0.25;
	lr=h[0][10]*(1 + stepsize*(random() - 0.5));
		if (lr > 0.75)
			lr=0.75;	/* reset to the limit */
		if (lr < 0.25)
			lr=0.25;

	/* computation section of the walk */
xs=2.0;				/* p.u. synch impedance */
eaf=sqrt(1 + xs*xs + 2*xs*0.6); /* 0.6 is sin(Á), pwr factor angle,
	eaf is p.u. internal voltage at full load */

xs1=ks[1]*ks[1];
xs5=(ks[5]*ks[5]/25);
xs7=(ks[7]*ks[7]/49);
xsal=(5*ls*PI*ds/18);
g=h[0][5];
r1=r+g;
while(test>.001)  {
	xpal=12.*BR*r*ks[1]*xs/(MU*js*SSF*ls*ds*r1*r1*PI);
	g1=12.*(xs1 + xs5 + xs7)/p/PI*(1./(xpal-xsal));


	test=fabs(g-g1)/g1;
	g=g1;
	r1=r+g;
	printf("\ntest=%lf,\tg=%lf",test,g);
}

if (g < GMIN)
	continue;
if (xs > 2.0)
	continue;
```

```
jrnl=(BR*g*p)/(2*MU*RSF*r*dr*lr*kr[1]); /* noload rotor current density */
jr=eaf*jrnl;
if (jr > JRMAX)
      continue;


l=(minpwr*p)/(2*BR*w*ks[1]*r*SSF*ds*PI*(r+g)*ls*js*PF);  /* active length
*/

va=2*PI*r*l*w*BR*ks[1]*js*SSF*(r+g)*ds*ls/p;     /* va rating */

siv = find_siv(l, r, g, ds, dcore, ls);   /* stator iron volume */
riv = l*PI*r*(r - 2*dr*lr);               /* rotor iron volume */
scv = 2*PI*(r+g)*ds*ls*(1 + 2.3094*PI*(r+g)*CP/p);
                                     /* stator copper volume */
rcv = 2*PI*r*dr*lr*(1 + 2.3094*PI*r/p);          /* rotor copper volume */
cw = (rcv + scv)*DCU;                     /* total copper weight */
loa = l + 4*(r+g);                        /* length over-all */
doa = 2*(r+g+ds+dcore);                   /* over-all-diameter */
vol = VOLALL*(loa*PI*doa*doa/4);          /* machine envelope volume */

wt = WTALL*(cw + D*(BRNGS*riv + siv));            /* machine weight in kg */
wt_iron = D*(riv + siv);                  /* iron weight only */

ph = 31.86225*BETA*freq*BR1*HC1*wt_iron/D;
      /* hysteresis loss in watts, uses iron weight of machine */

pe = (106236.9*NU*BSAT*BSAT*T1*T1*freq*freq*wt_iron)/(RHO*D);
      /* eddy current loss in watts, uses iron weight of machine */

i2r = 2.0*SSF*ds*CRHO*PI* (1 + 2.3094*PI*(r+g)*CP/p) *js*js*(r+g)*ls;
                              /* stator copper loss in watts */
                                  /* revised 1-12-87  */

i2rr = 2.0*RSF*dr*r*lr*jr*jr*CRHO*PI* (1 + 2.3094*PI*r/p);
                          /* rotor excitation losses, 1-12-87 */
i2r+=i2rr;                /* total copper losses */

effcy=(minpwr)/(minpwr + ph + pe + i2r);

ew=wt + ke*(1-effcy) + kv*vol;                   /* Effective weight */

h[i][1]=js;     h[i][2]=freq;   h[i][3]=w;      h[i][4]=r;      h[i][5]=g;
h[i][6]=dcore;  h[i][7]=ds;     h[i][8]=dr;     h[i][9]=ls;     h[i][10]=lr;
h[i][11]=vol;   h[i][12]=wt;    h[i][13]=ph;    h[i][14]=pe;    h[i][15]=i2r;
h[i][16]=va;    h[i][17]=effcy; h[i][18]=ew;    h[i][19]=l;     h[i][20]=jr;
h[i][21]=jrnl;  h[i][22]=xs;    h[i][23]=eaf;   h[i][24]=loa;   h[i][25]=doa;
      /* this section just changed all the variables in the "hold" array */

      ++i;                /* go to the next h[i][] */
      }

return;
}

print_out(best, p, minpwr, ke, kv, rpm)
```

```
	int best, p;
	double minpwr, ke, kv, rpm;
{
char outfile[14];
FILE *fpo, *fopen();
int i;
/*
printf("\nWhat is the name of the file where you want the output? ");
scanf("%s", outfile);	*/

fpo=fopen("syn.out", "w");

fprintf(fpo,"%d", p);
fprintf(fpo,"\n%lf", minpwr);
fprintf(fpo,"\n%lf", ke);
fprintf(fpo,"\n%lf", kv);
fprintf(fpo,"\n%lf", rpm);
for (i=1; i <= 25; ++i)
	fprintf(fpo,"\n%lf",b[best][i]);
fprintf(fpo, "\n");
fclose(fpo);
}



double find_siv(l, r, g, ds, dcore, ls)   double l, r, g, ds, dcore, ls;
{
double one, two, three, four;

one = (r+g+ds+dcore)*(r+g+ds+dcore) - (r+g)*(r+g);
two = 2*PI*(r+g)*ds*ls;
three = (r+g+ds+dcore)*(r+g+ds+dcore) - (r+g+ds)*(r+g+ds);

four = l*(PI*one - two) + PI*4*(r+g)*three;
return(four);
}
#define   MULTIPLIER   25173
#define   MODULUS      32768
#define   INCREMENT    13849
#define   MODFLT      32768.0
double random()
{
	extern long int seed;
	seed=(MULTIPLIER*seed+INCREMENT) % MODULUS;
	return(seed/MODFLT);
}
double swf(n)		/* stator winding factor */
	int n;		/* harmonic order */
	{
	double kp, kb;

	kp=cos(0.3142*n);	/* pitch factor, assumes 0.8 coil pitch */
	kb=(sin(0.5236*n))/(0.5236*n);		/* breadth factor, from
			Kirtley's "Basic Formulas ... " and assumes an
			electrical winding angle of 60- */
	return(kp*kb);
 }
```

```
double rwf(n)          /* rotor winding factor, same comments as swf() */
      int n;
      {
      double kp, kb;

      kp=1;
      kb=(sin(0.5236*n))/(0.5236*n);
      return(kp*kb);
      }
```

4. Synchronous Machine Off-Design-Point Efficiency Code: seff.c

seff.c calculates the efficiency of the motor whose characteristics are in the syn.out data file for 20%, 40%, 60%, 80% and 100% of rated speed. Screen output of current and power levels are provided for the designer to monitor the calculations.

4.1 Input Data File: syn.out

Seff.c was designed with the intent that it could be run in a batch type execution file (for example a MS DOS ".bat" file) in conjunction with either of the two synthesis programs discussed earlier. Therefore, the output file generated by those programs, syn.out is taken unchanged as the input file for seff.c. Upon completion of the run, the resulting speed dependent efficiencies are appended to the end of the file in order of increasing shaft rpm.

4.2 seff.c Program Listing

```
#include "stdio.h"
#include "def.h"
#include "math.h"
      /*  program name:  seff.c to find efficiency of synchronous machines
*/
      /*  works with only a single machine */
      /*  calculates efficiency at twenty percent intervals of rated motor
speed*/
main()
{
FILE *fopen(), *fp;
double r, jrnl, jr, js, ls, lr, dcore, ds, dr, g, w, l, xs, eaf, i2rr,
      va, ph, pe, i2r, vol, wt, effcy, ew, xs1, xs5, xs7, xsal, ks[8],
      siv, riv, wt_iron, find_siv(), pmeff, pmjs, pmrpm, dhp, rpm, minpwr,
      ke, kv, freq,fj;
extern double swf();
int j=1, f, p, i;
char infile[14];

printf("\nCalculates efficiency of a single motor.\n");

fp=fopen("syn.out","r");      /*opens synchronous design program output
file for input:
                        read only*/

fscanf(fp, "%d", &p);         /* input number of pole pairs */
fscanf(fp, "%lf", &minpwr);
minpwr *= 746.0;         /* now in watts */
fscanf(fp, "%lf", &ke);
fscanf(fp, "%lf", &kv);
fscanf(fp, "%lf", &rpm);
fscanf(fp, "%lf", &js);
```

```
fscanf(fp, "%lf", &freq);
fscanf(fp, "%lf", &w);
fscanf(fp, "%lf", &r);
fscanf(fp, "%lf", &g);
fscanf(fp, "%lf", &dcore);
fscanf(fp, "%lf", &ds);
fscanf(fp, "%lf", &dr);
fscanf(fp, "%lf", &ls);
fscanf(fp, "%lf", &lr);
fscanf(fp, "%lf", &vol);
fscanf(fp, "%lf", &wt);
fscanf(fp, "%lf", &ph);
fscanf(fp, "%lf", &pe);
fscanf(fp, "%lf", &i2r);
fscanf(fp, "%lf", &va);
fscanf(fp, "%lf", &efficy);
fscanf(fp, "%lf", &ew);
fscanf(fp, "%lf", &l);
fscanf(fp, "%lf", &jr);
fscanf(fp, "%lf", &jrnl);
fclose(fp);
for (i=1; i < 8; i+=2)              /* harmonic winding factors    */
      {
      ks[i =swf(i);
      }
xs1=ks[1 *ks[1 ;
xs5=(ks[5 *ks[5 /25);
xs7=(ks[7 *ks[7 /49);
xsal=(5*ls*PI*ds/18);
siv = find_siv(l, r, g, ds, dcore, ls);        /* stator iron volume */
riv = l*PI*r*(r - 2*dr*lr);                /* rotor iron volume */
wt_iron = D*(riv + siv);                   /* iron weight only */
xs=(MU*js*SSF*(r+g)*(r+g)*ds*PI*ls * (12*(xs1 + xs5 + xs7)/(PI*g*p) +
xsal))
                  /(12*r*BR*ks[1 ); /* p.u. synch impedance */

      /* calculate the variation in the power, shaft speed and current
using pump law
      relations*/
while (j <=5)
{
fj=(double)j;
dhp=fj*fj*fj*minpwr/125.;

pmrpm= fj*rpm/5.;
freq = pmrpm*p/60.0;                 /* max electrical frequency */
pmjs = js*dhp/minpwr;                /* PM stator current */
eaf=sqrt(1 +(fj*fj/25.)*xs*xs + 2.*(fj*xs/5.)*0.6); /* 0.6 is sin(Á), pwr
factor angle,
      eaf is p.u. internal voltage at full load */
jr=eaf*jrnl;                         /* jr full load, linear with eaf */
ph = 31.86225*BETA*freq*BR1*HC1*wt_iron/D;
      /* hysteresis loss in watts, uses iron weight of machine */
pe = (106236.9*NU*BSAT*BSAT*T1*T1*freq*freq*wt_iron)/(RHO*D);
      /* eddy current loss in watts, uses iron weight of machine */
i2r = 2.0*SSF*ds*CRHO*PI* (1 + 2.3094*PI*(r+g)*CP/p) *pmjs*pmjs*(r+g)*ls;
      /* stator copper loss in watts-changed 3-2-89 */
```

```
i2rr = 2.0*RSF*dr*r*lr*jr*jr*CRHO*PI* (1 + 2.3094*PI*r/p);
                        /* rotor excitation losses, 1-12-87 */
pmeff = dhp/(dhp + ph + pe + i2r + i2rr);

dhp =dnp/746.0;
fp=fopen("syn.out", "a");     /*reopen the output file to write the
efficiency, appending to
                        end of file*/
fprintf(fp,"\n%lf", pmeff);
fclose(fp);
printf("\n stator current = %lf, field current = %lf",pmjs,jr);   /*screen
output for comfort
                                                sake*/
printf("\n stator losses = %lf, field losses = %lf",i2r,i2rr);
printf("\n  Efficiency for %lf rpm and %lf hp is %lf",pmrpm,dhp, pmeff);
j=j+1;
}
}           /* end of main program */

double find_siv(l, r, g, ds, dcore, ls)
double l, r, g, ds, dcore, ls;
{
double one, two, three, four;

one = (r+g+ds+dcore)*(r+g+ds+dcore) - (r+g)*(r+g);
two = 2*PI*(r+g)*ds*ls;
three = (r+g+ds+dcore)*(r+g+ds+dcore) - (r+g+ds)*(r+g+ds);

four = l*(PI*one - two) + PI*4*(r+g)*three;
return(four);
}

double swf(n);          /* stator winding factor */
      int n;                 /* harmonic order */
      {
      double kp, kb;
      kp=cos(0.3142*n);        /* pitch factor, assumes 0.8 coil pitch */
      kb=(sin(0.5236*n))/(0.5236*n);          /* breadth factor, from
                Kirtley's "Basic Formulas ... " and assumes an
                electrical winding angle of 60 */
      return(kp*kb);
      }
```

5. Iso-Voltage Synchronous Motor Efficiency Design Program: seff2.c

seff2.c calculates the efficiency of the motor whose characteristics are in the syn.out data file as a function of terminal line voltage for ten even increments of speed between zero and the maximum speed the motor can attain for that voltage. Since the stator current is limited by the I^2R heat losses that can be dissapated by the motor, motor speed is limited by the top speed that can be attained for the power resulting from rated current andthe reduced voltage Ten equal voltage increments are used between zero and 100% rated voltage. Screen output of current and power levels are provided for the designer to monitor the calculations. This program was used to generate the iso-voltage curves presented in Chapter Five.

5.1 Input Data File: syn.out

Seff2.c was also designed with the intent that it could be run in a batch type execution file (for example a MS DOS ".bat" file) in conjunction with either of the two synthesis programs discussed earlier. Therefore, the output file generated by those programs, syn.out is taken unchanged as the input file for seff2.c. Output is again appended to the end of the syn.out in order of increasing voltage increment, with the efficiencies for that voltage presented in order of increasing shaft speed.

5.2 seff.c Program Listing

```
#include "stdio.h"
#include "def.h"
#include "math.h"
/*  program name:  seff.c to find efficiency of synchronous machines */
/*  works with only a single machine */

main()
{
FILE *fopen(), *fp;
double r, jrnl, jr, js, ls, lr, dcore, ds, dr, g, w, l, xs, eaf, i2rr,
      va, ph, pe, i2r, vol, wt, effcy, ew, xs1, xs5, xs7, xsal, ks[8],
      siv, riv, wt_iron, find_siv(), pmeff, pmjs, pmrpm, dhp, rpm, minpwr,
      ke, kv, freq,fj,fk,percentv,maxpwr,maxrpm;
```

```
extern double swf();
int j=1, f, p, i,k=1;
char infile[14];

for (i=1; i < 8; i+=2)              /* harmonic winding factors    */
      {
      ks[i]=swf(i);
      }
xs1=ks[1]*ks[1];
xs5=(ks[5]*ks[5]/25);
xs7=(ks[7]*ks[7]/49);
xsal=(5*ls*PI*ds/18);

printf("\nCalculates efficiency of a single motor.\n");

fp=fopen("syn.out","r");

fscanf(fp, "%d", &p);         /* input number of pole pairs */
fscanf(fp, "%lf", &minpwr);
minpwr *= 746.0;          /* now in watts */
fscanf(fp, "%lf", &ke);
fscanf(fp, "%lf", &kv);
fscanf(fp, "%lf", &rpm);
fscanf(fp, "%lf", &js);
fscanf(fp, "%lf", &freq);
fscanf(fp, "%lf", &w);
fscanf(fp, "%lf", &r);
fscanf(fp, "%lf", &g);
fscanf(fp, "%lf", &dcore);
fscanf(fp, "%lf", &ds);
fscanf(fp, "%lf", &dr);
fscanf(fp, "%lf", &ls);
fscanf(fp, "%lf", &lr);
fscanf(fp, "%lf", &vol);
fscanf(fp, "%lf", &wt);
fscanf(fp, "%lf", &ph);
fscanf(fp, "%lf", &pe);
fscanf(fp, "%lf", &i2r);
fscanf(fp, "%lf", &va);
fscanf(fp, "%lf", &effcy);
fscanf(fp, "%lf", &ew);
fscanf(fp, "%lf", &l);
fscanf(fp, "%lf", &jr);
fscanf(fp, "%lf", &jrnl);
fclose(fp);

siv = find_siv(l, r, g, ds, dcore, ls);         /* stator iron volume */
riv = l*PI*r*(r - 2*dr*lr);                /* rotor iron volume */
wt_iron = D*(riv + siv);                   /* iron weight only */
xs=(MU*js*SSF*(r+g)*(r+g)*ds*PI*ls * (12*(xs1 + xs5 + xs7)/(PI*g*p) +
xsal))
                  /(12*r*BR*ks[1]);       /* p.u. synch impedance */

while (k <=10)
{
fk=(double)k;
percentv=fk/10.;
```

```
maxpwr=minpwr*percentv;
maxrpm=rpm*(pow(percentv,1./3.));      /*this calculates the maximum rpm the
                                        % voltage used could generate at the
                                        maximum stator current*/
fp=fopen("syn.out", "a");
fprintf(fp,"\n\n%lf\n", percentv);
fprintf(fp,"%lf\n", maxrpm);
printf ("\nmaxrpm = %lf\n",maxrpm);
fclose(fp);

while (j <=10)
{
fj=(double)j;                          /*fj is the speed fraction of the max
rpm*/
dhp=fj*fj*fj*maxpwr/1000.;

pmrpm= fj*maxrpm/10.;
freq = pmrpm*p/60.0;                   /* max electrical frequency */
pmjs = js*dhp/maxpwr;                  /* PM stator current */
eaf=sqrt(percentv*percentv +(fj*fj/100.)*xs*xs + 2.*(fj*xs/10.)*0.6);
      /* 0.6 is sin(Á), pwr factor angle,
      eaf is p.u. internal voltage at full load */

jr=eaf*jrnl;                           /* jr full load, linear with eaf */
ph = 31.86225*BETA*freq*BR1*HC1*wt_iron/D;
      /* hysteresis loss in watts, uses iron weight of machine */
pe = (106236.9*NU*BSAT*BSAT*T1*T1*freq*freq*wt_iron)/(RHO*D);
      /* eddy current loss in watts, uses iron weight of machine */
i2r = 2.0*SSF*ds*CRHO*PI* (1 + 2.3094*PI*(r+g)*CP/p) *pmjs*pmjs*(r+g)*ls;
      /* stator copper loss in watts-changed 3-2-89 */
i2rr = 2.0*RSF*dr*r*lr*jr*jr*CRHO*PI* (1 + 2.3094*PI*r/p);
                              /* rotor excitation losses, 1-12-87 */
pmeff = dhp/(dhp + ph + pe + i2r + i2rr);

dhp =dhp/746.0;
fp=fopen("syn.out", "a");
fprintf(fp,"\n%lf", pmeff);
fclose(fp);
printf("\n stator current = %lf, field current = %lf",pmjs,jr);
printf("\n stator losses = %lf, field losses = %lf",i2r,i2rr);
printf("\n  Efficiency for %lf rpm and %lf hp is %lf",pmrpm,dhp, pmeff);
j=j+i;
}
j=1;
k=k+1;
}
}           /* end of main program */

double find_siv(l, r, g, ds, dcore, ls)
      double l, r, g, ds, dcore, ls;
{
double one, two, three, four;

one = (r+g+ds+dcore)*(r+g+ds+dcore) - (r+g)*(r+g);
two = 2*PI*(r+g)*ds*ls;
three = (r+g+ds+dcore)*(r+g+ds+dcore) - (r+g+ds)*(r+g+ds);
```

```
four = 1*(PI*one - two) + PI*4*(r+g)*three;
return(four);
}

double swf(n)           /* stator winding factor */
      int n;          /* harmonic order */
      {
      double kp, kb;
      kp=cos(0.3142*n);       /* pitch factor, assumes 0.8 coil pitch */
      kb=(sin(0.5236*n))/(0.5236*n);          /* breadth factor, from
                  Kirtley's "Basic Formulas ... " and assumes an
                  electrical winding angle of 60˚ */
      return(kp*kb);
      }
```

6. Definitions and Limitations Header File: def.h

def.h contains the constants, constraints and parameters that are used throughout the programs above. In general, values of any variable appearing in the code in all uppercase letters is defined in def.h. It should be noted that not all C libraries are consistent. For example, PI is defined in the Think C library, but not in the Microsoft C library. It is "commented" out in this listing to avoid a "double declaration" error statement on compilation.

6.1 def.h Program Listing

```
/*    file name:      def.h   */

                  /* list of general constants*/
/*#define           PI           3.141592654       */
#define             BSAT         1.5          /*max flux anywhere, Tesla*/
#define             MU           12.5664E-7    /*MU of air*/
#define             BR           1.05         /*air gap flux density, Tesla*/


                  /*magnetic iron constants*/

#define             D            7.65E3       /*density, kg/m3, of m19*/
#define             T1           0.014        /*first thickness, inch,M19*/
#define             RHO          52.          /*resistivity,micro-ohm-cm, M19*/
#define             BETA         2.5
#define             BR1          7.89   /*residual induction,kguass,M19 at
                                               BSAT and T1*/
#define             HC1          0.48         /*coercive force, oersteds, of
                                          M19 at BSAT and T1*/
#define             NU           2.0    /*anomalous loss factor of M19*/

                  /*machine constants*/

#define             MAX_TIP_SPEED     200.0        /*max allowable rotor
                                               tangential velocity,
                                               meters/second*/
#define             RMAX         2.0          /*maximum rotor radius, m*/
#define             JSMAX        12.E6 /      *maximum stator current density
                                                          A/m2*/
#define             JRMAX        15.E6        /*maximum rotor currentdensity*/
#define             PF           0.8          /*power factor of all machines,
                                               sine of angle psi = 0.6*/
#define             SSF          0.35         /* stator slot space factor*/
#define             RSF          0.35         /*rotor slot space factor*/
#define             CRHO         1.724E-8     /*copper resistivity*/
#define             DCU          8968.0             /*COPPER DENSITY*/
#define             GMIN         0.002        /*minimum machine gap*/
#define             CP           0.8          /*coil pitch*/
#define             BRNGS        1.03         /*rotor bearing weight allowance
                                          as % of rotor weight alone*/
#define             PSI          0.55         /*induction motor rated to
                                          pullouttorque ratio*/
#define             VOLALL       1.1          /*frame & foundation volume
                                          allowance*/
#define             WTALL        1.1          /*frame & foundation Weight
                                                     allowance*/
```

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